

SUBLATTICES OF ASSOCIAHEDRA AND PERMUTOHEDRA

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ABSTRACT. Grätzer asked in 1971 for a characterization of sublattices of Tamari lattices (*associahedra*). A natural candidate was coined by McKenzie in 1972 with the notion of a *bounded homomorphic image of a free lattice*—in short, *bounded lattice*. Urquhart proved in 1978 that every associahedron is bounded (thus so are its sublattices). Geyer conjectured in 1994 that every finite bounded lattice embeds into some associahedron.

We disprove Geyer’s conjecture, by introducing an infinite collection of lattice-theoretical identities that hold in every associahedron, but not in every finite bounded lattice. Among those finite counterexamples, there are the *permutohedron* on four letters $P(4)$, and in fact two of its subdirectly irreducible retracts, which are *Cambrian lattices of type A*.

For natural numbers m and n , we denote by $B(m, n)$ the (bounded) lattice obtained by doubling a join of m atoms in an $(m + n)$ -atom Boolean lattice. We prove that $B(m, n)$ embeds into an associahedron iff $\min\{m, n\} \leq 1$, and that $B(m, n)$ embeds into a permutohedron iff $\min\{m, n\} \leq 2$. In particular, $B(3, 3)$ cannot be embedded into any permutohedron. Nevertheless we prove that $B(3, 3)$ is a homomorphic image of a sublattice of the permutohedron on 12 letters.

1. INTRODUCTION

For every positive integer n , the set $A(n)$ of all binary bracketings of $n + 1$ symbols x_0, x_1, \dots, x_n can be partially ordered by the reflexive, transitive closure of the binary relation consisting of all the pairs (s, t) where t is obtained from s by replacing a subword of the form $(uv)v$ by $u(vw)$. The study of the poset $A(n)$ originates in Tamari [25], and is then pursued in many papers. In particular, Friedman and Tamari [9] prove that $A(n)$ is a *lattice*, that is, every pair x, y of elements has a least upper bound (join) $x \vee y$ and a greatest lower bound (meet) $x \wedge y$. The lattice $A(n)$ is called a *Tamari lattice* in Bennett and Birkhoff [2]. The elements of $A(n)$ are in one-to-one correspondence with the vertices of the *Stasheff polytope*, also called *associahedron*, so $A(n)$ is often called the *associahedron on n* .

Grätzer asked in Problem 6 of [12] (see also Problem I.1 of Grätzer [13]) for a characterization of all sublattices of associahedra. Soon after, McKenzie [20] introduced a lattice-theoretical property that later proved itself fundamental, namely being a *bounded homomorphic image of a free lattice* (see Section 2 for precise definitions). Since then the convention of calling such lattices *bounded lattices* (not to be confused with lattices with a least and a largest element) has established itself. Among the two simplest nondistributive lattices M_3 and N_5 (cf. Figure 1.1), N_5

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(on the right hand side of the picture) is bounded while M_3 (on the left hand side) is not.

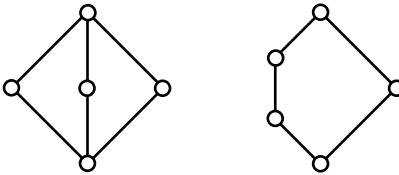


FIGURE 1.1. The lattices M_3 and N_5

Urquhart proved in [26, Corollary, page 55] that every associahedron is bounded. As every sublattice of a finite bounded lattice is bounded, it follows that M_3 cannot be embedded into any associahedron. On the other hand N_5 is itself an associahedron (namely $A(3)$), and every distributive lattice with n join-irreducible elements can be embedded into $A(n + 1)$ (cf. Markowsky [18, page 288]). This led to a plausible conjecture as to which lattices can be embedded into some associahedron, namely:

Can every finite bounded lattice be embedded into some associahedron?

This conjecture was first stated in Geyer [10, page 106].

Finite bounded lattices are exactly those that can be obtained, starting with the one-element lattice, by applying a finite sequence of instances of the so-called *doubling construction* on closed intervals (see Freese, Ježek, and Nation [8, Corollary 2.44]). At the bottom of the hierarchy of bounded lattices, we can find those obtained by doubling a point (viewed as a one-element interval) in a finite Boolean lattice. Denote by $B(m, n)$ the lattice obtained by doubling the join of m atoms in an $(m + n)$ -atom Boolean lattice (cf. Section 9). We prove in Corollary 10.7 that $B(m, n)$ embeds into some associahedron iff $\min\{m, n\} \leq 1$. This settles Geyer's conjecture in the negative.

Our proof involves the construction of an infinite collection of lattice-theoretical identities, the *Gaspacho identities* (Section 7). We prove that every associahedron satisfies all Gaspacho identities (Theorem 7.1). The simplest Gaspacho identity, $Gzp(1, 1)$, is renamed (Veg_1) in Section 8, and we find there our first example of a finite bounded lattice that does not satisfy some Gaspacho identity (namely (Veg_1)). This lattice, denoted by $P_{\{3\}}(4)$ and represented on the right hand side of Figure 6.1, is a retract of $P(4)$. Thus, we infer that the permutohedron $P(4)$ has no lattice embedding into any associahedron: it does not satisfy the identity (Veg_1) satisfied by every associahedron. More generally, we introduce a family of lattices $P_U(n)$, for $U \subseteq \{1, \dots, n\}$, that are *retracts*—with respect to the lattice operations—of the *permutohedron* $P(n)$ on n letters, cf. Proposition 6.4. We establish with Proposition 6.9 the identity between our lattices $P_U(n)$ and Reading's *Cambrian lattices of type A* [22]. In particular we characterize the Cambrian lattices of type A as the quotients of permutohedra by their *minimal meet-irreducible congruences*.

As seen above, another source of finite bounded lattices that cannot be embedded into any associahedron is provided by the lattices $B(m, n)$, for $\min\{m, n\} \geq 2$. We introduce in Section 9 a weakening, denoted by (Veg_2) , of $Gzp(2, 2)$, that is not satisfied by $B(2, 2)$ (Corollary 9.3). Hence $B(2, 2)$ is another counterexample to Geyer's conjecture. This lattice is represented in the right hand side of Figure 9.1.

Our negative embedding result for the permutohedron $P(4)$ raises the analogue of Geyer’s question for permutohedra: namely, *can every finite bounded lattice be embedded into some permutohedron?* Again, it is known that every permutohedron is bounded (cf. Caspard [5]). As every associahedron $A(n)$ is a sublattice (and, in fact, a *retract*, see Corollary 6.5) of the corresponding permutohedron $P(n)$, every sublattice of an associahedron is also a sublattice of a permutohedron. We disprove the question above in Theorem 11.1, by proving that *the lattice $B(3, 3)$ cannot be embedded into any permutohedron*. Our proof starts with the observation that as $B(3, 3)$ is subdirectly irreducible, if it embeds into some permutohedron $P(\ell)$, then it embeds into some Cambrian lattice $P_U(\ell)$.

Unlike our negative solution of Geyer’s conjecture, which involves an *identity* that holds in all associahedra but not in $B(2, 2)$, our negative embedding result for $B(3, 3)$ does not produce an identity. There is a good reason for this. Namely, $B(3, 3)$ is, using terminology from McKenzie [20], *splitting* (which means finite, bounded, and subdirectly irreducible), hence there is a lattice-theoretical identity that holds in a lattice L iff $B(3, 3)$ does not belong to the lattice variety generated by L . Such an identity is constructed, using known algorithms, in (12.1). Then, with the assistance of the software **Prover9** – **Mace4**, we show that the Cambrian lattice $P_U(12)$, for $U := \{5, 6, 9, 10, 11\}$, does not satisfy that identity. In particular, this shows that although $B(3, 3)$ satisfies all the identities satisfied by all permutohedra (and even all the identities satisfied by $P(12)$), it cannot be embedded into any permutohedron. Hence, our negative embedding result for $B(3, 3)$ (Theorem 11.1) cannot be proved *via* a separating identity.

2. NOTATION AND TERMINOLOGY

We set

$$\begin{aligned} [n] &:= \{1, \dots, n\}, \\ \mathcal{I}_n &:= \{(i, j) \in [n] \times [n] \mid i < j\}, \\ \Delta_n &:= \{(i, i) \mid i \in [n]\}, \end{aligned}$$

for each natural number n .

For a subset X in a poset P , we set

$$\begin{aligned} P \downarrow X &:= \{p \in P \mid (\exists x \in X)(p \leq x)\}, \\ P \Downarrow X &:= \{p \in P \mid (\exists x \in X)(p < x)\}, \\ P \uparrow X &:= \{p \in P \mid (\exists x \in X)(p \geq x)\}; \end{aligned}$$

furthermore, we set $P \downarrow x := P \downarrow \{x\}$, $P \Downarrow x := P \Downarrow \{x\}$, and $P \uparrow x := P \uparrow \{x\}$, for each $x \in X$. For subsets X and Y of P , we say that X *refines* Y , in notation $X \ll Y$, if $X \subseteq P \downarrow Y$. For elements $a, b \in P$, we set

$$\begin{aligned} [a, b] &:= \{p \in P \mid a \leq p \leq b\}, \\ [a, b[&:= \{p \in P \mid a \leq p < b\}, \\]a, b] &:= \{p \in P \mid a < p \leq b\}, \\]a, b[&:= \{p \in P \mid a < p < b\}. \end{aligned}$$

Here we stray away from the usual convention of denoting intervals in the form $[a, b)$ or $(a, b]$ for half-open intervals and (a, b) for open intervals. The reason for this is

that the present paper involves the notations (a, b) (for pairs of elements), $]a, b[$ (for open intervals), and $\langle a, b \rangle$ (for join-irreducible elements in associahedra).

We shall denote by P^{op} the poset with the same underlying set as P but ordering reversed.

A lattice L is *join-semidistributive* if $x \vee y = x \vee z$ implies that $x \vee y = x \vee (y \wedge z)$, for all $x, y, z \in L$. *Meet-semidistributivity* is defined dually, and *semidistributivity* is the conjunction of join-semidistributivity and meet-semidistributivity. A *lattice term* is obtained from variables by repeatedly composing the meet and the join operations, so for example $(x \wedge y) \vee (x \vee z)$ is a lattice term (we shall use lower case Sans Serif fonts, such as x, y, z, u, v, \dots , for either variables or terms). A (lattice-theoretical) *identity* is a statement of the form $u = v$ (or $u \leq v$, equivalent to $u = u \wedge v$) for lattice terms u and v . A lattice L *satisfies the identity* $u = v$ if $u(\vec{a}) = v(\vec{a})$ for each assignment \vec{a} from the variables of either u or v to the elements of L . A *variety of lattices* is the class of all lattices that satisfy a given set of identities.

A nonzero element p in L is *join-irreducible* if $p = \bigvee X$ implies that $p \in X$ for each finite nonempty subset X of L . Meet-irreducible elements are defined dually. We denote by $\text{Ji}(L)$ (resp., $\text{Mi}(L)$) the set of all join-irreducible (resp., meet-irreducible) elements of L . A *lower cover* of an element $p \in L$ is an element $x < p$ in L such that $]x, p[= \emptyset$. Upper covers are defined dually. We denote by p_* (resp., p^*) the lower cover (resp., upper cover) of p in case it exists and it is unique. For a finite lattice L , $\text{Ji}(L)$ is exactly the set of all the elements of L that have a unique lower cover; and dually for $\text{Mi}(L)$. In that case, we define binary relations \nearrow and \searrow on L by setting

$$\begin{aligned} x \nearrow y &\iff (y \in \text{Mi}(L) \text{ and } x \not\leq y \text{ and } x \leq y^*), \\ y \searrow x &\iff (x \in \text{Ji}(L) \text{ and } x \not\leq y \text{ and } x_* \leq y), \end{aligned}$$

for all $x, y \in L$. Then L is meet-semidistributive iff for each $p \in \text{Ji}(L)$, there exists a largest element $u \in L$ such that $u \searrow p$; this element is then denoted by $\kappa_L(p)$, or $\kappa(p)$ in case L is understood, and it is meet-irreducible (cf. Freese, Ježek, and Nation [8, Theorem 2.56]). A similar statement holds for join-semidistributivity and $\kappa^{\text{op}}(u)$, for $u \in \text{Mi}(L)$, instead of meet-semidistributivity and $\kappa(p)$, for $p \in \text{Ji}(L)$.

The *join-dependency relation* is the binary relation \mathbf{D}_L on L defined by $a \mathbf{D}_L q$, or $a \mathbf{D} q$ in case L is understood, by

$$a \mathbf{D}_L q \iff (q \in \text{Ji}(L) \text{ and } a \neq q \text{ and } (\exists x \in L)(a \leq q \vee x \text{ and } a \not\leq q_* \vee x)), \quad (2.1)$$

for all $a, q \in L$. A *join-cover* of $a \in L$ is a finite subset $C \subseteq L$ such that $a \leq \bigvee C$. A join-cover C of a is *nontrivial* if $a \notin L \downarrow C$. A join-cover C of a is *minimal* if, for every join-cover D of a , $D \ll C$ implies $C \subseteq D$. It is well known [8, Lemma 2.31] that, if L is a finite lattice and $a, q \in L$,

$$a \mathbf{D}_L q \iff \text{there exists a minimal nontrivial join-cover } C \text{ of } a \text{ such that } q \in C.$$

A surjective homomorphism $f: K \twoheadrightarrow L$ is *bounded* if $f^{-1}\{x\}$ has a least and a largest element, for each $x \in L$. McKenzie recognized in [20] the fundamental role played by lattices which are *bounded homomorphic images of free lattices*. Since then, those lattices have been mostly called *bounded lattices*. Every bounded lattice is semidistributive (apply [8, Theorem 2.20] and its dual), but the converse fails, even for finite lattices (see the example represented in [8, Figure 5.5]). Bounded lattices are called *congruence-uniform* in Reading [21], unfortunately the latter

terminology is also in use for lattices in which all congruence classes, with respect to any given congruence, have the same cardinality, so we shall use here the widely established “bounded” terminology here.

A finite lattice L is bounded iff the join-dependency relation is cycle-free on the join-irreducible elements of both L and L^{op} (cf. [8, Corollary 2.39]). The finite bounded lattices are exactly those that can be obtained by starting from the one-element lattice and then applying a finite succession of the so-called *doubling operation* on closed intervals, cf. Freese, Ježek, and Nation [8, Theorem 2.44].

As shown by the following result from Freese, Ježek, and Nation [8, Lemma 11.10], the relation \mathbf{D}_L can be easily obtained from the arrow relations between $\text{Ji}(L)$ and $\text{Mi}(L)$.

Lemma 2.1. *Let p, q be distinct join-irreducible elements in a finite lattice L . Then $p \mathbf{D}_L q$ iff there exists $u \in \text{Mi}(L)$ such that $p \nearrow u \searrow q$.*

3. BASIC CONCEPTS ABOUT PERMUTOHEDRA

Throughout this section we shall define permutohedra in a way suited to our needs (Definition 3.1) and relate that definition to those of some earlier works. We fix a natural number n .

A subset \mathbf{x} of \mathcal{I}_n is *closed* if it is transitive (viewed as a binary relation): that is, $(i, j) \in \mathbf{x}$ and $(j, k) \in \mathbf{x}$ implies that $(i, k) \in \mathbf{x}$, for all $i, j, k \in [n]$. A subset \mathbf{x} of \mathcal{I}_n is *open* (resp., *clopen*), if $\mathcal{I}_n \setminus \mathbf{x}$ is closed (resp., both \mathbf{x} and $\mathcal{I}_n \setminus \mathbf{x}$ are closed).

Definition 3.1. The *permutohedron of index n* , denoted by $\mathbf{P}(n)$, is the set of all clopen subsets of \mathcal{I}_n , partially ordered by inclusion.

The term *permutohedron* was first coined in Guilbaud and Rosenstiehl [14], and widely used since then.

The permutohedron was first defined in terms of the group \mathfrak{S}_n of all permutations of $[n]$, for each positive integer n . We set $\text{Inv}(\sigma) := \{(i, j) \in \mathcal{I}_n \mid \sigma^{-1}(i) > \sigma^{-1}(j)\}$ for each $\sigma \in \mathfrak{S}_n$, the *set of inversions* of σ . The following result is a straightforward exercise.

Lemma 3.2. *Let $\sigma, \tau \in \mathfrak{S}_n$. Then $\text{Inv}(\sigma) = \text{Inv}(\tau)$ iff $\sigma = \tau$.*

The following result is contained in Yanagimoto and Okamoto [27, Proposition 2.2].

Proposition 3.3. *The set $\text{Inv}(\sigma)$ is a clopen subset of \mathcal{I}_n , for each $\sigma \in \mathfrak{S}_n$. Conversely, every clopen subset of \mathcal{I}_n is the set of inversions of some permutation of $[n]$ (necessarily unique by Lemma 3.2).*

It follows from Lemma 3.2 and Proposition 3.3 that one can define a partial ordering on \mathfrak{S}_n by setting

$$\sigma \leq \tau \Leftrightarrow \text{Inv}(\sigma) \subseteq \text{Inv}(\tau), \text{ for all } \sigma, \tau \in \mathfrak{S}_n,$$

and this partial ordering is isomorphic to the permutohedron $\mathbf{P}(n)$ (cf. Definition 3.1).

As every intersection of closed sets is closed, every union of open sets is open. For a subset \mathbf{x} of \mathcal{I}_n , we shall denote by $\text{int}(\mathbf{x})$ (resp., $\text{cl}(\mathbf{x})$) the largest open subset

of \mathbf{x} (resp., the least closed set containing \mathbf{x}). Hence $\text{cl}(\mathbf{x})$ is the transitive closure of \mathbf{x} , while

$$\text{int}(\mathbf{x}) = \{(i, j) \in \mathcal{I}_n \mid (\forall m > 0)(\forall i = s_0 < s_1 < \dots < s_m = j) \\ (\exists l < m)((s_l, s_{l+1}) \in \mathbf{x})\}. \quad (3.1)$$

The following lemma, see Santocanale [23, Lemma 2.6], is crucial in establishing Proposition 3.5. It is implicit in the proof of Yanagimoto and Okamoto [27, Theorem 2.1].

Lemma 3.4. *The set $\text{cl}(\mathbf{x})$ is open, for each open $\mathbf{x} \subseteq \mathcal{I}_n$. Dually, the set $\text{int}(\mathbf{x})$ is closed, for each closed $\mathbf{x} \subseteq \mathcal{I}_n$.*

From Lemma 3.4 it follows that for all $\mathbf{x}, \mathbf{y} \in \mathcal{P}(n)$, there exists a largest element of $\mathcal{P}(n)$ contained in $\mathbf{x} \cap \mathbf{y}$, namely $\text{int}(\mathbf{x} \cap \mathbf{y})$. Dually, there exists a least element of $\mathcal{P}(n)$ that contains $\mathbf{x} \cup \mathbf{y}$, namely $\text{cl}(\mathbf{x} \cup \mathbf{y})$. Therefore, we get the following result, first established in Guilbaud and Rosenstiehl [14, Section VI.A], see also Yanagimoto and Okamoto [27, Theorem 2.1].

Proposition 3.5. *The poset $\mathcal{P}(n)$ is a lattice. The meet and the join in $\mathcal{P}(n)$ are given by*

$$\mathbf{x} \wedge \mathbf{y} = \text{int}(\mathbf{x} \cap \mathbf{y}), \quad \mathbf{x} \vee \mathbf{y} = \text{cl}(\mathbf{x} \cup \mathbf{y}),$$

for all $\mathbf{x}, \mathbf{y} \in \mathcal{P}(n)$.

Hence, the permutohedron $\mathcal{P}(n)$ it is often called the *lattice of all permutations of n letters*.

Proposition 3.6. *The lattice $\mathcal{P}(n)$ is complemented. Moreover, the assignment $\mathbf{x} \mapsto \mathbf{x}^c := \mathcal{I}_n \setminus \mathbf{x}$ defines an involutive dual automorphism of $\mathcal{P}(n)$ that sends each clopen subset \mathbf{x} to a lattice-theoretical complement of \mathbf{x} in $\mathcal{P}(n)$.*

The least element of $\mathcal{P}(n)$ is \emptyset , it is the set of inversions of the identity permutation. The largest element of $\mathcal{P}(n)$ is \mathcal{I}_n ; it is the set of inversions of the permutation $i \mapsto n + 1 - i$.

4. JOIN-IRREDUCIBLE ELEMENTS IN THE PERMUTOHEDRON

Throughout this section we shall fix a natural number n . We shall describe the join- and meet-irreducible elements of $\mathcal{P}(n)$, state a few lemmas needed for further sections, and indicate how they imply Caspard's result that all permutohedra are bounded.

Notation 4.1. We set $\mathcal{D}_n := \{(a, b, U) \mid (a, b) \in \mathcal{I}_n, U \subseteq [a, b], a \notin U, \text{ and } b \in U\}$, and, for each $(a, b, U) \in \mathcal{D}_n$, we set

$$\langle a, b; U \rangle := \mathcal{I}_n \cap ([a, b] \setminus U \times U).$$

The following description of the join-irreducible elements in the lattice $\mathcal{P}(n)$ is contained in Santocanale [23, Section 4], see in particular Example 4.10 of that paper. By using Proposition 3.6, the description of meet-irreducible elements follows.

Lemma 4.2. *The join-irreducible (resp., meet-irreducible) elements of $\mathcal{P}(n)$ are exactly those of the form $\langle a, b; U \rangle$ (resp., $\langle a, b; U \rangle^c$), for $(a, b, U) \in \mathcal{D}_n$.*

Lemma 4.3. *The equality $\langle a, b; U \rangle_* = \langle a, b; U \rangle \setminus \{(a, b)\}$ holds, for each triple $(a, b, U) \in \mathcal{D}_n$.*

Characterizations of the table of $P(n)$, that is, the order between join-irreducible elements and meet-irreducible elements, and of both relations \searrow and \nearrow appear in Duquenne and Cherfouh [7, Lemma 9] and Caspard [4, Proposition 2], respectively. The previous description of the join-irreducible elements by triples from \mathcal{D}_n yields the following lemma in a straightforward way.

Lemma 4.4. *Let $(a, b, U) \in \mathcal{D}_n$. Set $\tilde{U} := ([a, b] \setminus U) \cup \{b\}$. Then $x \searrow \langle a, b; U \rangle$ iff $x \leq \langle a, b; \tilde{U} \rangle^c$, for each $x \in P(n)$.*

Consequently, we obtain that for each $(c, d; V) \in \mathcal{D}_n$, $\langle c, d; V \rangle^c$ lies above $\langle a, b; U \rangle_*$ but not above $\langle a, b; U \rangle$ iff $\langle a, b; \tilde{U} \rangle \leq \langle c, d; V \rangle$, that is, $c \leq a < b \leq d$ and $\tilde{U} = V \cap [a, b]$. It follows that $\kappa_{P(n)}(\langle a, b; U \rangle) = \langle a, b; \tilde{U} \rangle^c$. By using [8, Theorem 2.56], it follows that $P(n)$ is meet-semidistributive. As $P(n)$ is self-dual, we obtain that it is semidistributive. This result was first obtained simultaneously by Duquenne and Cherfouh [7, Theorem 3] and Le Conte de Poly-Barbut [17, Lemme 9] (in the latter paper the result was extended to all *Coxeter lattices*).

We set

$$U \upharpoonright [i, j] := (U \cap [i, j]) \cup \{j\}, \quad \text{for all } U \subseteq [n] \text{ and all } (i, j) \in \mathcal{I}_n. \quad (4.1)$$

By using Lemma 2.1 together with Lemmas 3.6 and 4.4, we obtain the following characterization of the join-dependency relation on $P(n)$. This characterization was obtained in Santocanale [23, Example 4.10].

Proposition 4.5. *Let $(a, b, U), (c, d, V) \in \mathcal{D}_n$. Then the relation $\langle a, b; U \rangle \mathbf{D} \langle c, d; V \rangle$ holds in $P(n)$ iff $[c, d] \not\subseteq [a, b]$ and $V = U \upharpoonright [c, d]$.*

This implies trivially that the join-dependency relation on $P(n)$ is a strict ordering on $\text{Ji}(P(n))$. In particular, this relation has no cycle. As $P(n)$ is self-dual (cf. Lemma 3.6), we obtain the following result from Caspard [5, Theorem 1].

Theorem 4.6. *The lattice $P(n)$ is bounded.*

It is noteworthy to observe the following characterization of minimal join-covers in $P(n)$, which can be obtained as a consequence of Proposition 4.5. Although we will make no direct use of Proposition 4.7, the authors of the present paper found this result useful in coining the relevant notion of a *U-polarized measure* introduced in Definition 10.1.

Proposition 4.7. *For $(a, b, U) \in \mathcal{D}_n$, the minimal join-covers C of $\langle a, b; U \rangle$ are exactly those of the form*

$$C = \{ \langle z_i, z_{i+1}; U \upharpoonright [z_i, z_{i+1}] \rangle \mid i < k \},$$

where k is a positive integer and $a = z_0 < z_1 < \dots < z_k = b$.

5. THE LATTICES $P_U(n)$ AND ASSOCIAHEDRA

In this section we shall introduce the lattices $P_U(n)$, that will turn out later to be the *Cambrian lattices of type A* (cf. Proposition 6.9), and the associahedra $A(n)$ as particular cases. We shall relate our definition of $A(n)$ with the one used by Huang and Tamari [15], and verify that there are arbitrarily large 3-generated sublattices of associahedra (Proposition 5.3). We shall also verify that every lattice $P_U(n)$ is a sublattice of the corresponding $P(n)$ (Corollary 5.6).

Observe from Definition 3.1 that for a positive integer n , the permutohedron $P(n)$ consists of all the transitive subsets $\mathbf{a} \subseteq \mathcal{J}_n$ such that

$$(x, z) \in \mathbf{a} \text{ implies that either } (x, y) \in \mathbf{a} \text{ or } (y, z) \in \mathbf{a}, \quad \text{for all } x < y < z \text{ in } [n].$$

When the choice whether $(x, y) \in \mathbf{a}$ or $(y, z) \in \mathbf{a}$ is determined by a subset U of $[n]$, we obtain the structures $P_U(n)$ defined below. Namely, let us denote by $D_U(n)$ the collection of all subsets \mathbf{a} of \mathcal{J}_n such that $1 \leq i < j < k \leq n$ and $(i, k) \in \mathbf{a}$ implies that $(i, j) \in \mathbf{a}$ in case $j \in U$ and $(j, k) \in \mathbf{a}$ in case $j \notin U$. Observe that, in order to define $D_U(n)$, we need only to know the interior $U \setminus \{1, n\}$, so $D_U(n) = D_{U \setminus \{1, n\}}(n)$.

Definition 5.1. We define $P_U(n)$ as the collection of all *transitive* members of $D_U(n)$, and we order $P_U(n)$ by set-theoretical inclusion. For $U = [n]$, we set $A(n) := P_{[n]}(n)$, the *associahedron on n* .

We first explain the terminology “associahedron”, for our structure $A(n)$, as follows. Denote by $A'(n)$ the set of all maps $f: [n] \rightarrow [n]$ such that

- $i \leq f(i)$, for each $i \in [n]$;
- $i \leq j \leq f(i)$ implies that $f(j) \leq f(i)$, for all $i, j \in [n]$.

We endow $A'(n)$ with the componentwise ordering.

Huang and Tamari proved in [15] that $A'(n)$ is isomorphic to the originally defined Tamari lattice, defined as the poset of all bracketings of $n + 1$ symbols given an ordering defined from certain natural rewriting rules (see the Introduction). Thus we will be entitled to call $A(n)$ a Tamari lattice, or an associahedron, once we establish the following simple result.

Proposition 5.2. *The posets $A(n)$ and $A'(n)$ are isomorphic, for every positive integer n .*

Proof. We define maps $\varphi: A(n) \rightarrow A'(n)$ and $\psi: A'(n) \rightarrow A(n)$ as follows:

- For each $\mathbf{x} \in A(n)$, $\varphi(\mathbf{x})$ is the map from $[n]$ to $[n]$ defined by

$$\varphi(\mathbf{x})(i) := \text{largest } j \in [i, n] \text{ such that } \{i\} \times]i, j] \subseteq \mathbf{x}, \quad \text{for each } i \in [n].$$
- For each $f \in A'(n)$, we define $\psi(f) := \{(i, j) \in \mathcal{J}_n \mid j \leq f(i)\}$.

It is a straightforward exercise to verify that these assignments define mutually inverse, order-preserving maps between $A(n)$ and $A'(n)$. \square

For a positive integer n , we define elements $\mathbf{a}_n, \mathbf{b}_n, \mathbf{c}_n \in A(n)$ by

$$\begin{aligned} \mathbf{a}_n &:= \langle 1, n \rangle, \\ \mathbf{b}_n &:= \bigcup (\langle i, i+1 \rangle \mid i \text{ even}, 1 \leq i < n), \\ \mathbf{c}_n &:= \bigcup (\langle i, i+1 \rangle \mid i \text{ odd}, 1 \leq i < n). \end{aligned}$$

It follows from the proof of Santocanale [23, Proposition 5.16] that the cardinality of the sublattice of $A(n)$ generated by $\{\mathbf{a}_n, \mathbf{b}_n, \mathbf{c}_n\}$ goes to infinity as n goes to infinity. Therefore,

Proposition 5.3. *There are arbitrarily large 3-generated sublattices of associahedra.*

In universal algebraic terms, Proposition 5.3 implies immediately that *the variety of lattices generated by all associahedra is not locally finite*.

Although we found the description of Tamari lattices by either $A(n)$ or $A'(n)$ more convenient for our present purposes, this is not the case for all applications. For example, bracket reversing in the original description of the Tamari lattice easily implies the well-known fact that $A(n)$ is *self-dual*. This self-duality is not apparent in either description of the Tamari lattice by $A(n)$ or $A'(n)$. It is implicit in Lemmas 8 and 9 of Urquhart [26], and stated in Bennett and Birkhoff [2, page 139].

The corresponding dual automorphism of $A'(n)$ can be described explicitly as follows. Extend each element $f \in A'(n)$ at the point 0 by setting $f(0) := n$. Observe that the conditions (i) and (ii) defining $A'(n)$ are still satisfied on $[0, n]$. Next, for each $f \in A'(n)$, define $\tilde{f}: [0, n] \rightarrow [0, n]$ by setting $\tilde{f}(0) := n$, and

$$\tilde{f}(i) := \text{least } j \in [i, n] \text{ such that } n - i < f(n - j), \quad \text{for each } i \in [n].$$

The proof of the following result is then an easy exercise.

Proposition 5.4. *The assignment $f \mapsto \tilde{f}$ defines an involutive dual automorphism of $A'(n)$.*

We come now to the structures $P_U(n)$. Clearly, $D_U(n)$ is a sublattice of the powerset lattice of \mathcal{J}_n ; in particular, it is distributive. Furthermore, $P_U(n)$ is a meet-subsemilattice of $D_U(n)$ containing the largest element (namely \mathcal{J}_n); in particular, it is a lattice.

A key point in understanding the lattice structure of $P_U(n)$ is the following analogue of Lemma 3.4.

Lemma 5.5. *The closure $\text{cl}(\mathbf{x})$ belongs to $P_U(n)$, for each $\mathbf{x} \in D_U(n)$. Consequently, $\text{cl}(\mathbf{x})$ is the least element of $P_U(n)$ containing \mathbf{x} .*

Proof. Let $i < j < k$ with $(i, k) \in \text{cl}(\mathbf{x})$. By definition, there are a positive integer m and $i = s_0 < s_1 < \dots < s_m = k$ such that $(s_u, s_{u+1}) \in \mathbf{x}$ for each $u < m$. Let $l < m$ such that $s_l < j \leq s_{l+1}$. If $j = s_{l+1}$, then the chain $i = s_0 < s_1 < \dots < s_{l+1} = j$ witnesses the relation $(i, j) \in \text{cl}(\mathbf{x})$. Now suppose that $j < s_{l+1}$. If $j \in U$, then $(s_l, j) \in \mathbf{x}$ and the chain $i = s_0 < s_1 < \dots < s_l < j$ witnesses the relation $(i, j) \in \text{cl}(\mathbf{x})$. If $j \notin U$, then $(j, s_{l+1}) \in \mathbf{x}$ and the chain $j < s_{l+1} < \dots < s_m = k$ witnesses the relation $(j, k) \in \text{cl}(\mathbf{x})$.

This completes the proof that $\text{cl}(\mathbf{x})$ belongs to $D_U(n)$. As $\text{cl}(\mathbf{x})$ is transitive, it thus belongs to $P_U(n)$. \square

Corollary 5.6. *The set $P_U(n)$ is a 0, 1-sublattice of $P(n)$. The meet and the join of elements $\mathbf{x}, \mathbf{y} \in P_U(n)$ are given by $\mathbf{x} \wedge \mathbf{y} = \mathbf{x} \cap \mathbf{y}$ and $\mathbf{x} \vee \mathbf{y} = \text{cl}(\mathbf{x} \cup \mathbf{y})$, respectively.*

From Theorem 4.6 and Corollary 5.6 it follows immediately that $P_U(n)$ is a bounded lattice, for each $U \subseteq [n]$. We shall verify in Proposition 6.9 that the lattices $P_U(n)$ are exactly the *Cambrian lattices of type A* introduced in Reading [22].

6. A SUBDIRECT DECOMPOSITION OF THE PERMUTOHEDRON

In this section we shall strengthen Corollary 5.6 by proving that every lattice $P_U(n)$ is a *retract* (with respect to the lattice operations) of the permutohedron $P(n)$. This result is obtained by introducing the general definition of *join-fitness* of a finite $(\vee, 0, 1)$ -semilattice within a larger finite lattice (Definition 6.2) and proving that $P_U(n)$ join-fits within $P(n)$. We shall also prove (Proposition 6.7) that every permutohedron $P(n)$ is a subdirect product of the corresponding $P_U(n)$

and that the lattices $P_U(n)$ are exactly the Cambrian lattices of type A (Proposition 6.9).

Throughout this section we shall fix a positive integer n .

The following lemma gives a convenient description of the join-irreducible elements of $P_U(n)$, which involves the restriction operation defined in (4.1). Its proof is a straightforward exercise.

Lemma 6.1. *For any $(i, j) \in \mathcal{I}_n$, the least element of $P_U(n)$ containing (i, j) as an element is $\langle i, j \rangle_U := \langle i, j; U \upharpoonright [i, j] \rangle$. Consequently,*

$$\text{Ji}(P_U(n)) = \{ \langle i, j \rangle_U \mid (i, j) \in \mathcal{I}_n \}.$$

Notational convention. For the case $U = [n]$, we shall write $\langle i, j \rangle$ instead of $\langle i, j \rangle_{[n]}$, the join-irreducible elements of the associahedron $A(n)$.

The lattices $A(4) = P_{[4]}(4)$ and $P_{\{3\}}(4)$ are represented on the left hand side and right hand side of Figure 6.1, respectively. On these pictures, we mark the join-irreducible elements by doubled circles and we write ij instead of $\langle i, j \rangle_U$.

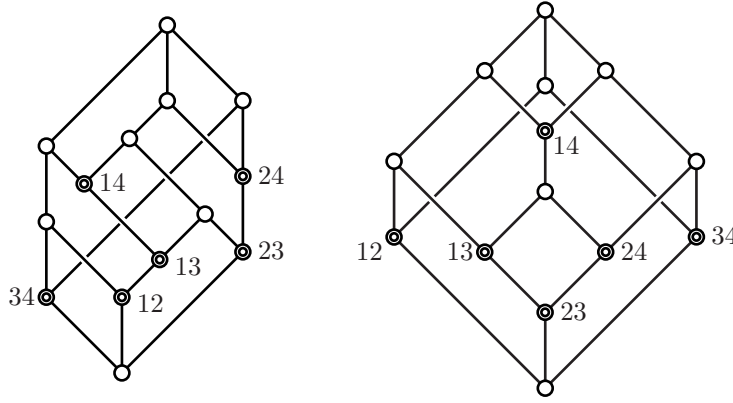


FIGURE 6.1. The lattices $A(4)$ and $P_{\{3\}}(4)$

In order to establish that every $P_U(n)$ is a retract of the corresponding permutahedron $P(n)$, it is convenient to introduce the following concept.

Definition 6.2. We say that a $(\vee, 0, 1)$ -subsemilattice K of a finite lattice L *join-fits within L* if

$$(\forall (p, q) \in \text{Ji}(K) \times \text{Ji}(L))(p \mathbf{D}_L q \Rightarrow q \in K).$$

Lemma 6.3. *Let K be a lattice that join-fits within a finite lattice L . Then the lower projection map $(\pi: L \rightarrow K, y \mapsto \text{largest } x \in K \text{ such that } x \leq y)$ is a surjective lattice homomorphism.*

Proof. It is obvious that π is a surjective meet-homomorphism. Now let $y_0, y_1 \in L$, we must prove that $\pi(y_0 \vee y_1) \leq \pi(y_0) \vee \pi(y_1)$. It suffices to prove that for each $p \in \text{Ji}(K)$, if $p \leq y_0 \vee y_1$, then $p \leq \pi(y_0) \vee \pi(y_1)$. The result is trivial if either $p \leq y_0$ or $p \leq y_1$, so suppose from now on that $p \not\leq y_0$ and $p \not\leq y_1$. As $p \leq y_0 \vee y_1$, there exists a minimal nontrivial join-cover I of p in L refining $\{y_0, y_1\}$. It follows that $I = I_0 \cup I_1$, where we set $I_k := I \downarrow y_k$ for each $k \in \{0, 1\}$. For each $k < 2$ and each $q \in I_k$, the relation $p \mathbf{D}_L q$ holds, thus, by assumption, $q \in K$. From

$q \leq y_k$ and $q \in K$ it follows that $q \leq \pi(y_k)$; thus $\bigvee I_k \leq \pi(y_k)$ as well. Therefore, $p \leq \bigvee I_0 \vee \bigvee I_1 \leq \pi(y_0) \vee \pi(y_1)$. \square

Proposition 6.4. *The lattice $P_U(n)$ join-fits within $P(n)$, for every positive integer n and every $U \subseteq [n]$. Consequently, $P_U(n)$ is a lattice-theoretical retract of $P(n)$.*

Proof. It follows from Corollary 5.6 that $P_U(n)$ is a 0, 1-sublattice (thus, *a fortiori*, a $(\vee, 0, 1)$ -subsemilattice) of $P(n)$. Now let $\mathbf{p} \in \text{Ji}(P_U(n))$ and $\mathbf{q} \in \text{Ji}(P(n))$ such that $\mathbf{p} \mathbf{D}_{P(n)} \mathbf{q}$. By Lemma 6.1, there exists $(a, b) \in \mathcal{I}_n$ such that $\mathbf{p} = \langle a, b; U \upharpoonright [a, b] \rangle$. By Lemma 4.2 and Proposition 4.5, there exists $(c, d) \in \mathcal{I}_n$ such that $[c, d] \subsetneq [a, b]$ and $\mathbf{q} = \langle c, d; (U \upharpoonright [a, b]) \upharpoonright [c, d] \rangle$. Thus $\mathbf{q} = \langle c, d; U \upharpoonright [c, d] \rangle$ belongs to $\text{Ji}(P_U(n))$, which completes the proof of the join-fitness statement. The retractness statement then follows from Corollary 5.6. \square

For $U := [n]$, we obtain the following corollary.

Corollary 6.5. *The associahedron $A(n)$ is a lattice-theoretical retract of the permutohedron $P(n)$, for every positive integer n .*

We shall verify soon (cf. Proposition 6.9) that the lattices $P_U(n)$ are exactly the Cambrian lattices associated to $P(n)$. Assuming this result, Proposition 6.4 gives an alternative proof of Reading's result [22, Theorem 6.5] that the Cambrian lattices of type A are retracts of the corresponding permutohedra. Let us notice that, while Reading simply states that Cambrian lattices of type A are sublattices of the corresponding permutohedra, his proof actually exhibits these sublattices as retracts. The analogous statement for associahedra (Corollary 6.5) was already observed in Björner and Wachs [3, Theorem 9.6].

The method of proof of Lemma 6.4 yields immediately the following.

Lemma 6.6. *The equality $\text{Ji}(P_U(n)) = P_U(n) \cap \text{Ji}(P(n))$ holds, and $\mathbf{p} \mathbf{D}_{P_U(n)} \mathbf{q}$ iff $\mathbf{p} \mathbf{D}_{P(n)} \mathbf{q}$, for all $\mathbf{p}, \mathbf{q} \in \text{Ji}(P_U(n))$. Furthermore, $\langle a, b \rangle_U \mathbf{D}_{P_U(n)} \langle c, d \rangle_U$ iff $[c, d] \subsetneq [a, b]$, for all $(a, b), (c, d) \in \mathcal{I}_n$.*

Denote by $\pi_U: P(n) \rightarrow P_U(n)$ the canonical projection (defined by $\pi_U(\mathbf{x}) :=$ largest element of $P_U(n)$ contained in \mathbf{x}). By Proposition 6.4, π_U is a lattice homomorphism.

Proposition 6.7. *Every lattice $P_U(n)$ is subdirectly irreducible, and the diagonal map $\pi: P(n) \rightarrow \prod (P_U(n) \mid U \subseteq [n])$, $\mathbf{x} \mapsto (\pi_U(\mathbf{x}) \mid U \subseteq [n])$ is a subdirect product decomposition of the permutohedron $P(n)$.*

Proof. It follows from Lemma 6.6 that $\langle 1, n \rangle_U$ is the least join-irreducible element of $P_U(n)$ with respect to the transitive closure of the relation $\mathbf{D}_{P_U(n)}$. Consequently, by Freese, Ježek, and Nation [8, Corollary 2.37], $P_U(n)$ is subdirectly irreducible.

It remains to prove that the map π is one-to-one. Let $\mathbf{a}, \mathbf{b} \in P(n)$ such that $\mathbf{a} \not\leq \mathbf{b}$. By Lemma 4.2, there exists $(i, j, U) \in \mathcal{D}_n$ such that the element $\mathbf{p} := \langle a, b; U \rangle$ is contained in \mathbf{a} but not in \mathbf{b} . Now $\mathbf{p} = \langle a, b \rangle_U$ belongs to $\text{Ji}(P_U(n))$, thus $\mathbf{p} \in \pi_U(\mathbf{a}) \setminus \pi_U(\mathbf{b})$, and thus $\pi_U(\mathbf{a}) \not\subseteq \pi_U(\mathbf{b})$. \square

For a join-irreducible element p in a finite lattice L , we set

$\Theta_L(p) :=$ least congruence of L that identifies p and p_* ,

$\Psi_L(p) :=$ largest congruence of L that does not identify p and p_* .

We shall also write $\Theta(p)$, $\Psi(p)$ in case the lattice L is understood. It follows from Freese, Ježek, and Nation [8, Theorem 2.30] that the join-irreducible congruences of L are exactly those of the form $\Theta_L(p)$, while the meet-irreducible congruences of L are exactly those of the form $\Psi_L(p)$.

The following lemma gives a description of the kernel of π_U in terms of the join-irreducible elements of $\mathbf{P}(n)$.

Lemma 6.8. *The kernel of π_U is equal to $\Psi_{\mathbf{P}(n)}(\langle 1, n; U \rangle)$, for each $U \subseteq [n]$.*

Proof. Since the definition of $\mathbf{P}_U(n)$ depends only of $U \setminus \{1, n\}$, we may assume that $1 \notin U$ and $n \in U$, that is, $(1, n, U) \in \mathcal{D}_n$. Set $\theta := \text{Ker } \pi_U$ and $\mathbf{p} := \langle 1, n; U \rangle$. As \mathbf{p} belongs to $\mathbf{P}_U(n)$, $\pi_U(\mathbf{p}) = \mathbf{p} > \mathbf{p}_* \geq \pi_U(\mathbf{p}_*)$, thus $\mathbf{p} \not\equiv \mathbf{p}_* \pmod{\theta}$. Conversely, we need to prove that every congruence ψ of $\mathbf{P}(n)$ such that $\mathbf{p} \not\equiv \mathbf{p}_* \pmod{\psi}$ is contained in θ . We may assume that ψ is join-irreducible, so $\psi = \Theta_{\mathbf{P}(n)}(\mathbf{q})$, with $\mathbf{q} = \langle c, d; V \rangle$ for some $(c, d, V) \in \mathcal{D}_n$ (cf. Lemma 4.2).

Denoting by \trianglelefteq the reflexive and transitive closure of the relation $\mathbf{D}_{\mathbf{P}(n)}$, $\mathbf{p} \not\equiv \mathbf{p}_* \pmod{\psi}$ means that $\mathbf{p} \not\trianglelefteq \mathbf{q}$ (cf. Freese, Ježek, and Nation [8, Lemma 2.36]), that is, using Proposition 4.5, $V \neq U \upharpoonright [c, d]$. It follows easily that \mathbf{q} does not belong to $\mathbf{P}_U(n)$, thus $\pi_U(\mathbf{q}) \leq \mathbf{q}_*$, $\pi_U(\mathbf{q}) = \pi_U(\mathbf{q}_*)$, so $(\mathbf{q}, \mathbf{q}_*) \in \theta$, that is, $\psi \subseteq \theta$. \square

We shall now verify that the lattices $\mathbf{P}_U(n)$ are identical to the *Cambrian lattices of type A* introduced in Reading [22]. We shall first recall how the latter are defined. For an integer $n \geq 2$ (if $n = 1$ then everything is trivial), we set $s_i := (i \ i+1)$ for $1 \leq i < n$. The Dynkin diagram of \mathfrak{S}_n is the undirected graph having as vertices the s_i and, as edges, the pairs $\{s_{i-1}, s_i\}$ for $i = 2, \dots, n-1$. Informally, an orientation of the Dynkin diagram of \mathfrak{S}_n consists of a choice, for each index $i \in [n-2]$, of an orientation between the two vertices s_i and s_{i+1} : that is, either $s_i \rightarrow s_{i+1}$ or $s_i \leftarrow s_{i+1}$. Hence the orientation is encoded by a subset of $\{2, 3, \dots, n-1\}$, namely

$$U := \{i+1 \mid 1 \leq i \leq n-2 \text{ and } s_i \rightarrow s_{i+1}\}.$$

The *Cambrian congruence* associated to U is the lattice congruence η of $\mathbf{P}(n)$ generated by all pairs $s_{i+1} \equiv s_{i+1}s_i \pmod{\eta}$ if $i+1 \in U$, and $s_i \equiv s_i s_{i+1} \pmod{\eta}$ if $i+1 \notin U$. Now, identifying a permutation with its set of inversions as defined in Section 3, we obtain that the Cambrian congruence η is generated by the pairs

$$\begin{aligned} \{(i+1, i+2)\} &\equiv \{(i+1, i+2), (i, i+2)\} \pmod{\eta}, & \text{if } i+1 \in U, \\ \{(i, i+1)\} &\equiv \{(i, i+1), (i, i+2)\} \pmod{\eta}, & \text{if } i+1 \notin U. \end{aligned}$$

The associated *Cambrian lattice* is defined as $\mathbf{P}(n)/\eta$. The following result shows that the Cambrian lattices of type A are exactly the lattices $\mathbf{P}_U(n)$.

Proposition 6.9. *The Cambrian congruence associated to U is the kernel of π_U . Consequently, the associated Cambrian lattice is $\mathbf{P}_U(n)$.*

Proof. Set again $\theta := \text{Ker } \pi_U$.

Let $i \in [n-2]$. Suppose first that $i+1 \in U$. For each $\mathbf{x} \in \mathbf{P}_U(n)$ with $\mathbf{x} \subseteq \{(i+1, i+2), (i, i+2)\}$, the possibility that $(i, i+2) \in \mathbf{x}$ is ruled out for it would imply (as $i+1 \in U$) that $(i, i+1) \in \mathbf{x}$, a contradiction; hence $\mathbf{x} \subseteq \{(i+1, i+2)\}$, and hence

$$\{(i+1, i+2)\} \equiv \{(i+1, i+2), (i, i+2)\} \pmod{\theta}.$$

Similarly, we can prove that if $i + 1 \notin U$, then

$$\{(i, i + 1)\} \equiv \{(i, i + 1), (i, i + 2)\} \pmod{\theta}.$$

It follows that θ contains η .

In order to establish the converse containment, remember from Lemma 6.8 that θ is generated by all $\Theta(\mathbf{q})$, where $\mathbf{q} = \langle c, d; V \rangle \in \text{Ji}(\text{P}(n))$ with $(c, d, V) \in \mathcal{D}_n$ and $V \neq U \upharpoonright [c, d]$. Hence it suffices to prove that $\mathbf{q} \equiv \mathbf{q}_* \pmod{\eta}$ for each such \mathbf{q} . We separate cases. If $U \upharpoonright [c, d] \not\subseteq V$, pick i in the difference; observe that $c < i < d$. From $i \in U$ it follows that $\{(i, i + 1)\} \equiv \{(i, i + 1), (i - 1, i + 1)\} \pmod{\eta}$, that is, as $i \notin V$, $\langle i, i + 1 \rangle_V \equiv \langle i - 1, i + 1 \rangle_V \pmod{\eta}$. Thus, setting $\langle k, k \rangle_V := \emptyset$ for each k , we get

$$\mathbf{q} = \langle c, d \rangle_V \leq \langle c, i - 1 \rangle_V \vee \langle i - 1, i + 1 \rangle_V \vee \langle i + 1, d \rangle_V \equiv \mathbf{x} \pmod{\eta}$$

where we set $\mathbf{x} := \langle c, i - 1 \rangle_V \vee \langle i, i + 1 \rangle_V \vee \langle i + 1, d \rangle_V$. From $(c, d) \notin \mathbf{x}$ it follows that $\mathbf{q} \not\subseteq \mathbf{x}$, thus $\mathbf{q} \equiv \mathbf{q}_* \pmod{\eta}$, as desired. The proof in case $V \not\subseteq U \upharpoonright [c, d]$ is similar, now picking an index $i \in V \setminus (U \upharpoonright [c, d])$ and obtaining, this time, elements $\mathbf{y}, \mathbf{y}' \in \text{P}(n)$ such that $(i, d) \notin \mathbf{y}$ and $\mathbf{q} \leq \mathbf{y}' \equiv \mathbf{y} \pmod{\eta}$. \square

As the elements $\langle 1, n \rangle_U$ are exactly the *minimal* elements of $\text{Ji}(\text{P}(n))$ with respect to the transitive closure \leq of the join-dependency relation, it follows from Freese, Ježek, and Nation [8, Lemma 2.36] that the Cambrian lattices of type A are exactly the quotients of permutohedra by their *minimal meet-irreducible congruences*. That is, *the Cambrian lattices of type A are exactly the maximal subdirectly irreducible quotients of permutohedra*.

The following consequence of Lemma 6.8 can be obtained, *via* Proposition 6.9, from Reading [22, Theorem 3.5]. We show here an easy, direct argument.

Corollary 6.10. *The lattices $\text{P}_U(n)$ and $\text{P}_{[n] \setminus U}(n)$ are dually isomorphic, for each $U \subseteq [n]$.*

Proof. Denote by $\gamma: \text{P}(n) \rightarrow \text{P}(n)$, $\mathbf{x} \mapsto \mathbf{x}^c$ the canonical dual automorphism (cf. Proposition 3.6). Again, we may assume that $1 \notin U$ and $n \in U$. Set $\mathbf{p} := \langle 1, n; U \rangle$, $\tilde{U} := ([1, n] \setminus U) \cup \{n\}$ and $\mathbf{q} := \langle 1, n; \tilde{U} \rangle$. As observed after the statement of Lemma 4.4, $\kappa_{\text{P}(n)}(\mathbf{p}) = \gamma(\mathbf{q})$. It follows that the prime interval $[\mathbf{p}_*, \mathbf{p}]$ projects up to the interval $[\gamma(\mathbf{q}), \gamma(\mathbf{q})^*]$, hence, as γ is a dual automorphism and using Lemma 6.8, $\text{Ker } \pi_U = \gamma(\text{Ker } \pi_{\tilde{U}})$, and hence $\text{P}_U(n) \cong \text{P}(n)/\text{Ker } \pi_U$ is dually isomorphic to $\text{P}(n)/\text{Ker } \pi_{\tilde{U}} \cong \text{P}_{\tilde{U}}(n) = \text{P}_{[n] \setminus U}(n)$. \square

In particular, as the associahedron $\text{A}(n)$ is self-dual, it is isomorphic to both $\text{P}_{\emptyset}(n)$ and to $\text{P}_{[n]}(n)$.

7. THE GAZPACHO IDENTITIES

In this section we shall construct an infinite collection of lattice-theoretical identities, the *Gazpacho identities*, and prove that these identities hold in every associahedron (Theorem 7.1).

We denote by \mathbb{S} the set of all finite sequences $\vec{m} = (m_1, \dots, m_d)$ of positive integers with $d \geq 2$, and we set

$$\mathfrak{F}(\vec{m}) := \prod ([m_i] \mid 1 \leq i \leq d), \quad \text{for each } \vec{m} \in \mathbb{S}.$$

We also define terms \mathbf{a}_i , $\tilde{\mathbf{b}}_i$, $\mathbf{e}_{\vec{m}}$, $\mathbf{e}_{\vec{m}}^*$ in the variables $\mathbf{a}_{i,j}$ and \mathbf{b}_i (for $1 \leq i \leq d$ and $1 \leq j \leq m_i$) by

$$\begin{aligned} \mathbf{a}_i &:= \bigvee_{j=1}^{m_i} \mathbf{a}_{i,j}, & \tilde{\mathbf{b}}_i &:= \left(\bigvee_{i'=1}^d \mathbf{b}_{i'} \right) \wedge (\mathbf{a}_i \vee \mathbf{b}_i) \quad (\text{for } 1 \leq i \leq d), \\ \mathbf{e}_{\vec{m}} &:= \bigwedge_{i=1}^d (\mathbf{a}_i \vee \mathbf{b}_i), & \mathbf{e}_{\vec{m}}^* &:= \left(\bigvee_{i'=1}^d \mathbf{b}_{i'} \right) \wedge \mathbf{e}_{\vec{m}} = \bigwedge_{i=1}^d \tilde{\mathbf{b}}_i. \end{aligned} \quad (7.1)$$

Further, we define lattice terms $\mathbf{f}_i^{\sigma,\tau}$, for $2 \leq i \leq d$ and $(\sigma, \tau) \in \mathfrak{S}_d \times \mathfrak{F}(\vec{m})$, by downward induction on i (for $2 \leq i < d$), by

$$\begin{aligned} \mathbf{f}_d^{\sigma,\tau} &:= (\mathbf{a}_{\sigma(d),\tau\sigma(d)} \vee \tilde{\mathbf{b}}_{\sigma(1)}) \wedge (\mathbf{a}_{\sigma(d)} \vee \mathbf{b}_{\sigma(d)}), \\ \mathbf{f}_i^{\sigma,\tau} &:= (\mathbf{a}_{\sigma(i),\tau\sigma(i)} \vee \tilde{\mathbf{b}}_{\sigma(1)}) \wedge (\mathbf{a}_{\sigma(i)} \vee \mathbf{b}_{\sigma(i)}) \wedge \bigwedge_{i < j \leq d} (\mathbf{a}_{\sigma(i),\tau\sigma(i)} \vee \mathbf{f}_j^{\sigma,\tau}). \end{aligned} \quad (7.2)$$

Let $\text{Gzp}(\vec{m})$ (the *Gazpacho identity with index \vec{m}*) be the following lattice-theoretical identity, in the variables $\mathbf{a}_{i,j}$ and \mathbf{b}_i , for $1 \leq i \leq d$ and $1 \leq j \leq m_i$:

$$\mathbf{e}_{\vec{m}} \leq \mathbf{e}_{\vec{m}}^* \vee \bigvee (\mathbf{f}_2^{\sigma,\tau} \mid (\sigma, \tau) \in \mathfrak{S}_d \times \mathfrak{F}(\vec{m})). \quad (\text{Gzp}(\vec{m}))$$

Theorem 7.1. *Every associahedron satisfies $\text{Gzp}(\vec{m})$ for each $\vec{m} \in \mathbb{S}$.*

Proof. Let ℓ be a positive integer. Set $\vec{m} = (m_1, \dots, m_d)$ with $d \geq 2$ and let $\mathbf{a}_{i,j}$ and \mathbf{b}_i (for $1 \leq i \leq d$ and $1 \leq j \leq m_i$) be elements of $\mathbf{A}(\ell)$. We define $\mathbf{b} := \bigvee_{i=1}^d \mathbf{b}_i$, and, applying the lattice polynomials defined above, elements \mathbf{a}_i , $\tilde{\mathbf{b}}_i$, $\mathbf{e} := \mathbf{e}_{\vec{m}}(\vec{\mathbf{a}}, \vec{\mathbf{b}})$, $\mathbf{f}_i^{\sigma,\tau} := \mathbf{f}_i^{\sigma,\tau}(\vec{\mathbf{a}}, \vec{\mathbf{b}})$, and

$$\mathbf{f} := (\mathbf{b} \wedge \mathbf{e}) \vee \bigvee (\mathbf{f}_2^{\sigma,\tau} \mid (\sigma, \tau) \in \mathfrak{S}_d \times \mathfrak{F}(\vec{m})).$$

We must prove that \mathbf{e} is contained in \mathbf{f} . Suppose otherwise and let $(x, y) \in \mathbf{e} \setminus \mathbf{f}$ with the interval $[x, y]$ minimal with that property. For each $i \in [d]$, there exists a subdivision

$$x = z_0^i < z_1^i < \dots < z_{n_i}^i = y \text{ with } (z_j^i, z_{j+1}^i) \in \bigcup_{k=1}^{m_i} \mathbf{a}_{i,k} \cup \mathbf{b}_i \text{ for each } j < n_i. \quad (7.3)$$

We set $Z_i := \{z_j^i \mid 0 \leq j \leq n_i\}$, for each $i \in [d]$. It follows from the minimality assumption on $[x, y]$ that $(x, z_j^i) \in \mathbf{f}$ for each $i \in [d]$ and each $j < n_i$. As $(x, y) \notin \mathbf{f}$, it follows that $(z_j^i, y) \notin \mathbf{f}$; in particular, $(z_{n_i-1}^i, y) \notin \mathbf{f}$. However, from $\mathbf{f}_2^{\sigma,\tau} \geq \mathbf{a}_{\sigma(2),\tau\sigma(2)}$ for each $(\sigma, \tau) \in \mathfrak{S}_d \times \mathfrak{F}(\vec{m})$ it follows that $\mathbf{a}_i \leq \mathbf{f}$, thus, *a fortiori*, $\bigcup_{k=1}^{m_i} \mathbf{a}_{i,k} \subseteq \mathbf{f}$, and thus, by (7.3), $(z_{n_i-1}^i, y) \in \mathbf{b}_i$.

Let $i \in [d]$. As $\mathbf{b}_i \subseteq \tilde{\mathbf{b}}_i$, there exists a least $z_i \in Z_i \setminus \{y\}$ such that $(z_i, y) \in \tilde{\mathbf{b}}_i$. If $z_i = x$, then (x, y) belongs to $\tilde{\mathbf{b}}_i \wedge \mathbf{e} = \mathbf{b} \wedge \mathbf{e}$, thus to \mathbf{f} , a contradiction; hence $x < z_i$. Pick $i_1 \in [d]$ such that $z_{i_1} \leq z_i$ for each $i \in [d]$. Denote by s_i the largest element of $Z_i \downarrow z_{i_1}$ and by s'_i the successor of s_i in Z_i , for each $i \in [d] \setminus \{i_1\}$. There exists a permutation $\sigma \in \mathfrak{S}_d$ such that $\sigma(1) = i_1$ and $s_{\sigma(2)} \leq s_{\sigma(3)} \leq \dots \leq s_{\sigma(d)}$.

Suppose that $(s_i, s'_i) \in \mathbf{b}_i$, for some $i \in [d] \setminus \{\sigma(1)\}$. From $s_i < z_{\sigma(1)} \leq s'_i$ it follows that $(s_i, z_{\sigma(1)}) \in \mathbf{b}_i$, thus, as $(z_{\sigma(1)}, y) \in \tilde{\mathbf{b}}_{\sigma(1)}$, we obtain that $(s_i, y) \in \mathbf{b}_i \vee \tilde{\mathbf{b}}_{\sigma(1)}$, thus $(s_i, y) \in \mathbf{b}$. From $\{s_i, y\} \subseteq Z_i$ it follows that $(s_i, y) \in \mathbf{a}_i \vee \mathbf{b}_i$, and so $(s_i, y) \in \mathbf{b} \wedge (\mathbf{a}_i \vee \mathbf{b}_i) = \tilde{\mathbf{b}}_i$, a contradiction as $s_i < z_i$. Therefore, $(s_i, s'_i) \notin \mathbf{b}_i$,

and therefore, by (7.3), there exists $\tau(i) \in [m_i]$ such that $(s_i, s'_i) \in \mathbf{a}_{i, \tau(i)}$. As $s_i < z_{\sigma(1)} \leq s'_i$, we also get $(s_i, z_{\sigma(1)}) \in \mathbf{a}_{i, \tau(i)}$.

From $(s_{\sigma(i)}, z_{\sigma(1)}) \in \mathbf{a}_{\sigma(i), \tau\sigma(i)}$ and $(z_{\sigma(1)}, y) \in \tilde{\mathbf{b}}_{\sigma(1)}$ it follows that $(s_{\sigma(i)}, y) \in \mathbf{a}_{\sigma(i), \tau\sigma(i)} \vee \tilde{\mathbf{b}}_{\sigma(1)}$. Moreover, from $\{s_{\sigma(i)}, y\} \subseteq Z_{\sigma(i)}$ it follows that $(s_{\sigma(i)}, y) \in \mathbf{a}_{\sigma(i)} \vee \mathbf{b}_{\sigma(i)}$, and therefore

$$(s_{\sigma(i)}, y) \in (\mathbf{a}_{\sigma(i), \tau\sigma(i)} \vee \tilde{\mathbf{b}}_{\sigma(1)}) \wedge (\mathbf{a}_{\sigma(i)} \vee \mathbf{b}_{\sigma(i)}). \quad (7.4)$$

Now we prove, by downward induction on i , that $(s_{\sigma(i)}, y) \in \mathbf{f}_i^{\sigma, \tau}$, for each $i \in [2, d]$. The case $i := d$ follows readily from (7.4). Now suppose that $2 \leq i < d$ and that $(s_{\sigma(j)}, y) \in \mathbf{f}_j^{\sigma, \tau}$ for each j with $i < j \leq d$. Fix such a j . From $(s_{\sigma(i)}, z_{\sigma(1)}) \in \mathbf{a}_{\sigma(i), \tau\sigma(i)}$ and $s_{\sigma(i)} \leq s_{\sigma(j)} < z_{\sigma(1)}$ it follows that $(s_{\sigma(i)}, s_{\sigma(j)}) \in \Delta_\ell \cup \mathbf{a}_{\sigma(i), \tau\sigma(i)}$. By induction hypothesis, it follows that $(s_{\sigma(i)}, y) \in \mathbf{a}_{\sigma(i), \tau\sigma(i)} \vee \mathbf{f}_j^{\sigma, \tau}$. Therefore, meeting the right hand side of this relation over all j and then with the right hand side of (7.4), we obtain that $(s_{\sigma(i)}, y) \in \mathbf{f}_i^{\sigma, \tau}$, as desired.

In particular, $(s_{\sigma(2)}, y) \in \mathbf{f}_2^{\sigma, \tau} \subseteq \mathbf{f}$. By the minimality assumption on the interval $[x, y]$, the pair $(x, s_{\sigma(2)})$ belongs to \mathbf{f} , and so $(x, y) \in \mathbf{f}$, a contradiction. \square

Due to the complexity of the identities $\text{Gzp}(\vec{m})$ for general \vec{m} , we shall study some of their much simpler consequences instead.

8. A FIRST NONTRIVIAL IDENTITY FOR ALL ASSOCIAHEDRA

In this section we shall prove that the simplest Gazpacho identity does not hold in the Cambrian lattice $\mathbf{P}_{\{3\}}(4)$, thus providing our first counterexample to Geyer's conjecture.

Consider the identity $\text{Gzp}(\vec{m})$ with $\vec{m} := (1, 1)$. It has the four variables $\mathbf{a}_1, \mathbf{a}_2, \mathbf{b}_1, \mathbf{b}_2$, it involves the terms $\tilde{\mathbf{b}}_i := (\mathbf{b}_1 \vee \mathbf{b}_2) \wedge (\mathbf{a}_i \vee \mathbf{b}_i)$, for $i \in \{1, 2\}$, and $\mathbf{e} := (\mathbf{a}_1 \vee \mathbf{b}_1) \wedge (\mathbf{a}_2 \vee \mathbf{b}_2)$. As $\mathfrak{F}(\vec{m})$ is a singleton, the superscript τ becomes irrelevant in the term $\mathbf{f}_d^{\sigma, \tau}$ given in (7.2) (for $d := 2$), so we omit it, and then

$$\mathbf{f}_2^\sigma = (\mathbf{a}_{\sigma(2)} \vee \tilde{\mathbf{b}}_{\sigma(1)}) \wedge (\mathbf{a}_{\sigma(2)} \vee \mathbf{b}_{\sigma(2)}), \quad \text{for each } \sigma \in \mathfrak{S}_2.$$

Consequently, $\text{Gzp}(1, 1)$ is equivalent to the following identity:

$$(\mathbf{a}_1 \vee \mathbf{b}_1) \wedge (\mathbf{a}_2 \vee \mathbf{b}_2) \leq (\tilde{\mathbf{b}}_1 \wedge \tilde{\mathbf{b}}_2) \vee ((\mathbf{a}_1 \vee \tilde{\mathbf{b}}_2) \wedge (\mathbf{a}_1 \vee \mathbf{b}_1)) \vee ((\mathbf{a}_2 \vee \tilde{\mathbf{b}}_1) \wedge (\mathbf{a}_2 \vee \mathbf{b}_2)).$$

Now observing that $\mathbf{a}_i \vee \mathbf{b}_i = \mathbf{a}_i \vee \tilde{\mathbf{b}}_i$ in every lattice, we can cancel out the term $\tilde{\mathbf{b}}_1 \wedge \tilde{\mathbf{b}}_2$ and thus we obtain the following equivalent form of $\text{Gzp}(1, 1)$, which we shall denote by (Veg_1) :

$$(\mathbf{a}_1 \vee \mathbf{b}_1) \wedge (\mathbf{a}_2 \vee \mathbf{b}_2) \leq ((\mathbf{a}_1 \vee \mathbf{b}_1) \wedge (\mathbf{a}_1 \vee \tilde{\mathbf{b}}_2)) \vee ((\mathbf{a}_2 \vee \tilde{\mathbf{b}}_1) \wedge (\mathbf{a}_2 \vee \mathbf{b}_2)). \quad (\text{Veg}_1)$$

Hence, as a consequence of Theorem 7.1, we obtain the following result.

Corollary 8.1. *Every associahedron satisfies (Veg_1) .*

Theorem 8.2. *The permutohedron $\mathbf{P}(4)$ does not satisfy the identity (Veg_1) . In particular, it has no lattice embedding into any associahedron.*

Proof. By using Proposition 6.7, it suffices to prove that $\mathbf{P}_U(4)$ does not satisfy (Veg_1) for a suitable $U \subseteq [4]$. Take $U := \{3\}$ and define elements of $\mathbf{P}_U(4)$ by $\mathbf{a}_1 := \langle 1, 3 \rangle_U$, $\mathbf{a}_2 := \langle 2, 4 \rangle_U$, $\mathbf{b}_1 := \langle 3, 4 \rangle_U$, and $\mathbf{b}_2 := \langle 1, 2 \rangle_U$. Hence $\mathbf{a}_1 = \{(1, 3), (2, 3)\}$,

$\mathbf{a}_2 = \{(2, 3), (2, 4)\}$, $\mathbf{b}_1 = \{(3, 4)\}$, and $\mathbf{b}_2 = \{(1, 2)\}$. Furthermore, it is straightforward to verify that

$$\begin{aligned}\mathbf{a}_1 \vee \mathbf{b}_1 &= \{(1, 3), (1, 4), (2, 3), (2, 4), (3, 4)\}, \\ \mathbf{a}_2 \vee \mathbf{b}_2 &= \{(1, 2), (1, 3), (1, 4), (2, 3), (2, 4)\}, \\ \mathbf{a}_1 \vee \mathbf{b}_2 &= \{(1, 2), (1, 3), (2, 3)\}, \\ \mathbf{a}_2 \vee \mathbf{b}_1 &= \{(2, 3), (2, 4), (3, 4)\}, \\ \mathbf{a}_1 \vee \mathbf{a}_2 &= \{(1, 3), (2, 3), (2, 4)\},\end{aligned}$$

thus

$$\begin{aligned}\tilde{\mathbf{b}}_j &= \mathbf{b}_j, & \text{for all } j \in \{1, 2\}, \\ (\mathbf{a}_i \vee \tilde{\mathbf{b}}_1) \wedge (\mathbf{a}_i \vee \tilde{\mathbf{b}}_2) &= \mathbf{a}_i, & \text{for all } i \in \{1, 2\}, \\ (\mathbf{a}_1 \vee \mathbf{b}_1) \wedge (\mathbf{a}_2 \vee \mathbf{b}_2) &= \{(1, 3), (1, 4), (2, 3), (2, 4)\}.\end{aligned}$$

In particular, for that particular instance, (Veg_1) is not satisfied. \square

Remark 8.3. The proof of Theorem 8.2 shows that the Cambrian lattice $P_{\{3\}}(4)$ does not satisfy the identity (Veg_1) . Hence, by Corollary 6.10, the Cambrian lattice $P_{\{3\}}(4) = P_{[4] \setminus \{2\}}(4)$ does not satisfy the dual of the identity (Veg_1) . In particular, $P_{\{2\}}(4)$ cannot be embedded into any associahedron, either. The lattice $P_{\{3\}}(4)$ is represented on the right hand side of Figure 6.1.

Remark 8.4. Observe that for positive integers m and n , there is a lattice embedding from the product $A(m) \times A(n)$ into $A(m+n)$, obtained by sending (\mathbf{x}, \mathbf{y}) to $\mathbf{x} \cup \mathbf{y}'$ where $\mathbf{y}' := \{(m+i, m+j) \mid (i, j) \in \mathbf{y}\}$. (A similar comment applies to embedding $P(m) \times P(n)$ into $P(m+n)$.) As the permutohedron $P(3)$ is a subdirect product of two copies of the five-element modular nondistributive lattice N_5 (see Figure 8.1) and $N_5 \cong A(3)$, it follows that $P(3)$ embeds into $A(3) \times A(3)$, thus into $A(6)$.

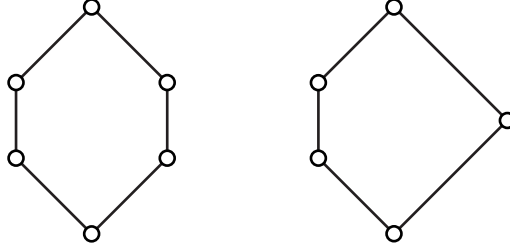


FIGURE 8.1. The lattices $P(3)$ and N_5

9. ANOTHER IDENTITY FOR ALL ASSOCIAHEDRA

In this section we shall prove that a weakening of a certain Gazpacho identity fails in the lattice $B(2, 2)$ (Corollary 9.3), thus providing our second counterexample to Geyer's conjecture.

Consider the Gazpacho identity $\text{Gzp}(\vec{m})$, where $\vec{m} := (2, 2)$, in which we substitute to both variables $\mathbf{a}_{1,j}$ and $\mathbf{a}_{2,j}$ the variable \mathbf{a}_j (not to be confused with the lattice term \mathbf{a}_i introduced in (7.1)), for $j \in \{1, 2\}$. By arguing in a similar manner

as at the beginning of Section 8, we see that the resulting identity is equivalent to the following identity, which we shall denote by (Veg_2) :

$$(a_1 \vee a_2 \vee b_1) \wedge (a_1 \vee a_2 \vee b_2) = \bigvee_{i,j \in \{1,2\}} ((a_i \vee \tilde{b}_j) \wedge (a_1 \vee a_2 \vee b_{3-j})), \quad (\text{Veg}_2)$$

with the lattice terms $\tilde{b}_j := (b_1 \vee b_2) \wedge (a_1 \vee a_2 \vee b_j)$, for $j \in \{1, 2\}$. Hence, as a consequence of Theorem 7.1, we obtain the following.

Theorem 9.1. *Every associahedron satisfies (Veg_2) .*

For natural numbers m and n , we denote by $B(m, n)$ the lattice obtained by doubling the join of m atoms in the $(m+n)$ -atom Boolean lattice. It can be obtained by adding a new element p to the Boolean lattice on $m+n$ atoms $a_1, \dots, a_m, b_1, \dots, b_n$, with the extra relations $a_i < p$ (for $1 \leq i \leq m$) and $p < a_1 \vee \dots \vee a_m \vee b_j$ (for $1 \leq j \leq n$). The lattices $B(1, 3)$ and $B(2, 2)$ are represented in Figure 9.1, with their join-irreducible elements marked by doubled circles.

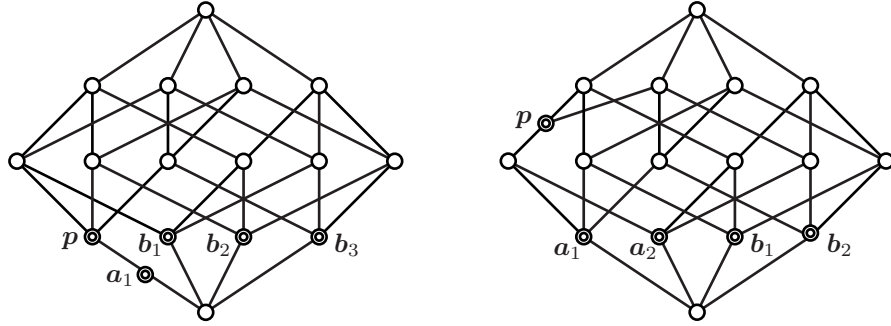


FIGURE 9.1. The lattices $B(1, 3)$ and $B(2, 2)$

The lattice $B(m, n)$ is a so-called *almost distributive lattice* (cf. Jipsen and Rose [16, Lemma 4.11]), and it is subdirectly irreducible (cf. [16, Theorem 4.17]). It is obtained by doubling a point from a finite Boolean lattice, thus it is bounded (cf. Freese, Ježek, and Nation [8, Theorem 2.44]).

The class of lattices of the form $B(m, n)$ is self-dual:

Lemma 9.2. *The lattices $B(m, n)$ and $B(n, m)$ are dually isomorphic, for all natural numbers m and n .*

Proof. Let x and y be disjoint sets of cardinality m and n , respectively, and denote by $B(x, y)$ the lattice obtained by doubling x in the powerset lattice $\mathfrak{P}(x \cup y)$ of $x \cup y$. Hence $B(x, y) = \mathfrak{P}(x \cup y) \cup \{p\}$ and $B(y, x) = \mathfrak{P}(x \cup y) \cup \{q\}$, for new elements p and q such that

$$\begin{aligned} x &< p \text{ and } p < x \cup \{j\} \text{ for each } j \in y, \\ y &< q \text{ and } q < \{i\} \cup y \text{ for each } i \in x. \end{aligned}$$

Define a map $\varphi: B(x, y) \rightarrow B(y, x)$ by $\varphi(x) := q$, $\varphi(p) := y$, and $\varphi(z) := (x \cup y) \setminus z$ for each $z \in \mathfrak{P}(x \cup y) \setminus \{x\}$. Then φ is a dual isomorphism. Now $B(m, n) \cong B(x, y)$ and $B(n, m) \cong B(y, x)$. \square

The evaluations in $B(2, 2)$ of the lattice terms \tilde{b}_1 and \tilde{b}_2 at the quadruple (a_1, a_2, b_1, b_2) are b_1 and b_2 , respectively, so the left hand side of (Veg_2) is evaluated by p while its right hand side is evaluated by $a_1 \vee a_2$. As these two elements are distinct, we obtain the following result.

Corollary 9.3. *The lattice $B(2, 2)$ does not satisfy the identity (Veg_2) . In particular, it cannot be embedded into any associahedron.*

Remark 9.4. It is not hard (although a bit tedious) to verify that $B(m, n)$ satisfies (Veg_1) for all non simultaneously zero natural numbers m and n . In particular, $B(2, 2)$ satisfies (Veg_1) but not (Veg_2) (cf. Corollary 9.3). On the other hand, $P(4)$ does not satisfy (Veg_1) (cf. Theorem 8.2) and it can be verified that it satisfies (Veg_2) . In particular, *none of the identities (Veg_1) and (Veg_2) implies the other.*

10. POLARIZED MEASURES AND MEET-HOMOMORPHISMS TO CAMBRIAN LATTICES

In the present section we shall introduce a convenient tool for handling lattice embeddings into Cambrian lattices of type A, inspired by the theory of Galois connections (cf. Gierz *et al.* [11] and the duality for finite lattices sketched in Santocanale [24]). We shall apply this tool by proving that $\min\{m, n\} \leq 1$ implies that $B(m, n)$ embeds into some associahedron (Theorem 10.7) and that $\min\{m, n\} \leq 2$ implies that $B(m, n)$ embeds into some Cambrian lattice of type A, thus in some permutohedron (Proposition 10.8).

We set $P^{[2]} := \{(x, y) \in P \times P \mid x < y\}$, for any poset P . Observe that $[n]^{[2]} = J_n$.

Definition 10.1. Let L be a join-semilattice, let P be a poset, and let $U \subseteq P$. An L -valued U -polarized measure on P is a map $\mu: P^{[2]} \rightarrow L$ such that

- (i) $\mu(x, z) \leq \mu(x, y) \vee \mu(y, z)$;
- (ii) $y \in U$ implies that $\mu(x, y) \leq \mu(x, z)$;
- (iii) $y \notin U$ implies that $\mu(y, z) \leq \mu(x, z)$,

for all $x < y < z$ in P . Furthermore, we say that μ satisfies the V -condition if for all $(x, y) \in P^{[2]}$ and all $a, b \in L$,

$$\text{if } \mu(x, y) \leq a \vee b, \text{ then} \tag{V}$$

there are $m \geq 1$ and a subdivision $x = z_0 < z_1 < \dots < z_m = y$ in P such that

$$\text{either } \mu(z_i, z_{i+1}) \leq a \text{ or } \mu(z_i, z_{i+1}) \leq b \text{ for each } i < m.$$

If (V) holds, then we shall say that *the refinement problem $\mu(x, y) \leq a \vee b$ can be solved in P* . In case $U = P$, we shall say *polarized measure* instead of U -polarized measure. Furthermore, if L has a least element 0, then we shall often extend the U -polarized measures by setting $\mu(x, x) := 0$ for each $x \in P$.

In all the cases that we will consider in this paper, P will be a finite chain, most of the time (but not always) of the form $[n]$ for a positive integer n . For the rest of this section we shall fix a positive integer n .

Example 10.2. Set $L := A(n)$. Then the assignment $\mu: (x, y) \mapsto \langle x, y \rangle$ defines an L -valued polarized measure on $[n]$. Furthermore, μ satisfies the V -condition and its range $(\vee, 0)$ -generates the lattice L .

Example 10.3. Set $L := P(n)$. Then the assignment $\mu: (x, y) \mapsto \langle x, y \rangle_U$ defines an L -valued U -polarized measure on $[n]$. Furthermore, μ satisfies the V-condition. However, its range does not $(\vee, 0)$ -generate L for $n \geq 3$.

Definition 10.4. Let $U \subseteq [n]$ and let L be a finite lattice. We say that maps $\mu: \mathcal{I}_n \rightarrow L$ and $\varphi: L \rightarrow P_U(n)$ are *dual* if $(x, y) \in \varphi(\mathbf{a})$ iff $\mu(x, y) \leq \mathbf{a}$, for all $(x, y) \in \mathcal{I}_n$ and all $\mathbf{a} \in L$.

We leave to the reader the straightforward proof of the following result.

Proposition 10.5. *The following statements hold, for any $U \subseteq [n]$ and any finite lattice L .*

- (i) *If $\mu: \mathcal{I}_n \rightarrow L$ and $\varphi: L \rightarrow P_U(n)$ are dual, then μ is an U -polarized measure and φ is a $(\wedge, 1)$ -homomorphism. Furthermore,*

$$\mu(x, y) = \text{least } \mathbf{a} \in L \text{ such that } (x, y) \in \varphi(\mathbf{a}), \quad \text{for each } (x, y) \in \mathcal{I}_n; \quad (10.1)$$

$$\varphi(\mathbf{a}) = \{(x, y) \in \mathcal{I}_n \mid \mu(x, y) \leq \mathbf{a}\}, \quad \text{for each } \mathbf{a} \in L. \quad (10.2)$$

- (ii) *Every $(\wedge, 1)$ -homomorphism $\varphi: L \rightarrow P_U(n)$ has a unique dual U -polarized measure $\mu: \mathcal{I}_n \rightarrow L$, which is defined by the formula (10.1).*
- (iii) *Every U -polarized measure $\mu: \mathcal{I}_n \rightarrow L$ has a unique dual $(\wedge, 1)$ -homomorphism $\varphi: L \rightarrow P_U(n)$, which is defined by the formula (10.2).*

Proposition 10.6. *Let $U \subseteq [n]$, let L be a finite lattice, and let $\mu: \mathcal{I}_n \rightarrow L$ and $\varphi: L \rightarrow P_U(n)$ be dual. The following statements hold:*

- (i) $\varphi(0) = \emptyset$ iff 0 does not belong to the range of μ .
- (ii) *The range of μ generates L as a $(\vee, 0)$ -subsemilattice iff φ is one-to-one.*
- (iii) μ satisfies the V-condition iff φ is a lattice homomorphism.

Proof. (i) is straightforward.

(ii). Suppose that φ is one-to-one and let $\mathbf{a} \in L$. It follows from Lemma 6.1 that there exists a decomposition $\varphi(\mathbf{a}) = \bigvee_{i=1}^m \langle x_i, y_i \rangle_U$ with a natural number m and elements $(x_i, y_i) \in \mathcal{I}_n$ for $1 \leq i \leq m$. Set $\mathbf{a}' := \bigvee_{i=1}^m \mu(x_i, y_i)$. From $(x_i, y_i) \in \varphi(\mathbf{a})$ it follows that $\mu(x_i, y_i) \leq \mathbf{a}$ for each i ; thus $\mathbf{a}' \leq \mathbf{a}$. Conversely, for each $i \in [m]$, $\mu(x_i, y_i) \leq \mathbf{a}'$, thus $(x_i, y_i) \in \varphi(\mathbf{a}')$, and thus, by Lemma 6.1, $\langle x_i, y_i \rangle_U \subseteq \varphi(\mathbf{a}')$. Therefore, $\varphi(\mathbf{a}) \subseteq \varphi(\mathbf{a}')$, thus, by assumption, $\mathbf{a} \leq \mathbf{a}'$, and thus $\mathbf{a} = \mathbf{a}'$ is a join of elements of the range of μ .

Conversely, suppose that the range of μ generates L as a join-semilattice and let $\mathbf{a}, \mathbf{b} \in L$ such that $\mathbf{a} \not\leq \mathbf{b}$. By assumption, there exists $(x, y) \in \mathcal{I}_n$ such that $\mu(x, y) \leq \mathbf{a}$ and $\mu(x, y) \not\leq \mathbf{b}$, that is, $(x, y) \in \varphi(\mathbf{a}) \setminus \varphi(\mathbf{b})$. Therefore, φ is one-to-one.

(iii). Suppose that φ is a join-homomorphism and let $(x, y) \in \mathcal{I}_n$ and $\mathbf{a}, \mathbf{b} \in L$ such that $\mu(x, y) \leq \mathbf{a} \vee \mathbf{b}$. This means that (x, y) belongs to $\varphi(\mathbf{a} \vee \mathbf{b}) = \varphi(\mathbf{a}) \vee \varphi(\mathbf{b}) = \text{cl}(\varphi(\mathbf{a}) \cup \varphi(\mathbf{b}))$, thus there exists a subdivision $x = z_0 < z_1 < \dots < z_m = y$ in $[n]$ such that $(z_i, z_{i+1}) \in \varphi(\mathbf{a}) \cup \varphi(\mathbf{b})$ for each $i < m$; that is, either $\mu(z_i, z_{i+1}) \leq \mathbf{a}$ or $\mu(z_i, z_{i+1}) \leq \mathbf{b}$. Therefore, μ satisfies the V-condition.

Conversely, suppose that μ satisfies the V-condition, let $\mathbf{a}, \mathbf{b} \in L$, and let $(x, y) \in \varphi(\mathbf{a} \vee \mathbf{b})$, we must prove that $(x, y) \in \varphi(\mathbf{a}) \vee \varphi(\mathbf{b})$. As μ and φ are dual, $\mu(x, y) \leq \mathbf{a} \vee \mathbf{b}$, thus, as μ satisfies the V-condition, there exists a subdivision $x = z_0 < z_1 < \dots < z_m = y$ in $[n]$ such that $\mu(z_i, z_{i+1})$ is contained in either \mathbf{a} or \mathbf{b} for each $i < m$; so $(z_i, z_{i+1}) \in \varphi(\mathbf{a}) \cup \varphi(\mathbf{b})$ for each $i < m$, and so $(x, y) \in \varphi(\mathbf{a}) \vee \varphi(\mathbf{b})$. \square

We apply Propositions 10.5 and 10.6 to the following two embedding results.

Theorem 10.7. *Let m and n be natural numbers. Then the lattice $B(m, n)$ embeds into some associahedron iff either $m \leq 1$ or $n \leq 1$.*

Proof. If $m \geq 2$ and $n \geq 2$, then $B(2, 2)$ embeds into $B(m, n)$, thus, by Theorem 9.3, $B(m, n)$ cannot be embedded into any associahedron. Hence, as every associahedron is self-dual and by Lemma 9.2, it suffices to prove that both $B(m, 0)$ and $B(m, 1)$ embed into $A(m + 2)$, for every positive integer m . As $B(m, 0)$ is distributive with $m + 1$ join-irreducible elements, the result for that lattice follows from Markowsky [18, page 288]. It remains to deal with $B(m, 1)$. It is convenient to describe the embedding by a polarized measure $\mu: \mathcal{J}_{m+2} \rightarrow B(m, 1)$. We set

$$\mathbf{a}_X := \bigvee_{i \in X} \mathbf{a}_i, \quad \text{for each } X \subseteq [m].$$

The measure $\mu: \mathcal{J}_{m+2} \rightarrow B(m, 1)$ is given (setting $\mathbf{b} := \mathbf{b}_1$) by

$$\begin{aligned} \mu(k, l) &:= \mathbf{a}_{[k, l-1]}, & \text{for } 1 \leq k < l \leq m+1, \\ \mu(k, m+2) &:= \mathbf{a}_{[k, m]} \vee \mathbf{b}, & \text{for } 2 \leq k \leq m+1, \\ \mu(1, m+2) &:= \mathbf{p}. \end{aligned}$$

It is straightforward to verify that μ is a polarized V-measure. The conclusion follows then from Propositions 10.5 and 10.6. \square

Proposition 10.8. *The lattice $B(m, 2)$ has a 0, 1-lattice embedding into the Cambrian lattice $P_{[m+2, 2m+1]}(2m+2)$, for every positive integer m .*

Proof. We shall define the embedding via a $[m+2, 2m+1]$ -polarized measure on $[2m+2]$, by using Propositions 10.5 and 10.6. It will be more convenient to construct the measure on the totally ordered set $\Lambda := [-m-1, m+1] \setminus \{0\}$ (which is isomorphic to the interval $[2m+2]$) and to prove that it is U -polarized with $U := [1, m]$.

We denote by $\mathbf{a}_1, \dots, \mathbf{a}_m, \mathbf{b}_1, \mathbf{b}_2$, and \mathbf{p} the join-irreducible elements of $B(m, 2)$, with $\bigvee_{1 \leq i \leq m} \mathbf{a}_i < \mathbf{p}$. We denote by $\mu: [0, m+1]^{[2]} \rightarrow B(m, 1)$ the polarized measure given by the isomorphism $[0, m+1] \cong [1, m+2]$ and the proof of Theorem 10.7. In particular, $\mu(i-1, i) = \mathbf{a}_i$ for $1 \leq i \leq m$, $\mu(m, m+1) = \mathbf{b}_1$, and $\mu(0, m+1) = \mathbf{p}$. Moreover, set $A := \{\mathbf{a}_i \mid 1 \leq i \leq m\}$.

We denote by $B'(m, 1)$ the copy of $B(m, 1)$, within $B(m, 2)$, obtained by changing \mathbf{b}_1 to \mathbf{b}_2 , and we denote by $\mu': [0, m+1]^{[2]} \rightarrow B'(m, 1)$ the corresponding polarized measure. In particular, $\mu'(i-1, i) = \mathbf{a}_i$ for $1 \leq i \leq m$, $\mu'(m, m+1) = \mathbf{b}_2$, and $\mu'(0, m+1) = \mathbf{p}$.

Now we define a map $\nu: \Lambda^{[2]} \rightarrow B(m, 2)$ as follows:

$$\begin{aligned} \nu(i, j) &:= \mu(i, j), & \text{for } 1 \leq i < j \leq m+1, \\ \nu(i, j) &:= \mu'(-j, -i), & \text{for } -m-1 \leq i < j \leq -1, \\ \nu(-i, j) &:= \mu(0, i \wedge j) = \mu'(0, i \wedge j), & \text{for } i, j \in [m+1]. \end{aligned}$$

We claim that ν is an U -polarized measure on Λ . Let $x < y < z$ in Λ , we need to prove that $\nu(x, z) \leq \nu(x, y) \vee \nu(y, z)$, while $y \in U$ implies that $\nu(x, y) \leq \nu(x, z)$ and $y \notin U$ implies that $\nu(y, z) \leq \nu(x, z)$.

If either $z < 0$ or $x > 0$, then the result follows from μ' and μ being U -polarized measures. Now assume that $x < 0$ and $z > 0$ and set $x' := -x$. Then $\nu(x, z) = \mu(0, x' \wedge z)$. If $y \in U$, then $\nu(x, y) = \mu(0, x' \wedge y) \leq \mu(0, x' \wedge z) = \nu(x, z)$. Further,

$x' \leq y$ implies that $x' \wedge y = x' \wedge z = x'$, thus $\mu(x' \wedge y, x' \wedge z) = 0 \leq \mu(y, z)$; while $y \leq x'$ implies that $\mu(x' \wedge y, x' \wedge z) = \mu(y, x' \wedge z) \leq \mu(y, z)$ (because μ is a polarized measure). In each case, $\mu(x' \wedge y, x' \wedge z) \leq \mu(y, z)$, so

$$\nu(x, z) = \mu(0, x' \wedge z) \leq \mu(0, x' \wedge y) \vee \mu(x' \wedge y, x' \wedge z) \leq \nu(x, y) \vee \nu(y, z).$$

If $y \notin U$, then the element $y' := -y$ belongs to U and $y' < x'$. Further, $\nu(y, z) = \mu'(0, y' \wedge z) \leq \mu'(0, x' \wedge z) = \nu(x, z)$. As above, $\mu'(y' \wedge z, x' \wedge z) \leq \mu'(y', x')$, so we obtain

$$\nu(x, z) = \mu'(0, x' \wedge z) \leq \mu'(0, y' \wedge z) \vee \mu'(y' \wedge z, x' \wedge z) \leq \nu(y, z) \vee \nu(x, y).$$

This completes the proof of ν being an U -polarized measure.

As $\nu(-m-1, m+1) = \mathbf{p}$, $\nu(-1, 1) = \mathbf{a}_1$, $\nu(m, m+1) = \mathbf{b}_1$, $\nu(-m-1, -m) = \mathbf{b}_2$, and $\nu(i, i+1) = \mathbf{a}_{i+1}$ for $1 \leq i \leq m-1$, the range of ν generates $\mathbf{B}(m, 2)$ as a $(\vee, 0)$ -semilattice. Now it remains to verify the V-condition. In order to do this, it suffices to prove that for every $(x, y) \in \Lambda^{[2]}$, every positive integer n , and every minimal join-covering in $\mathbf{B}(m, 2)$ of the form $\nu(x, y) \leq \bigvee_{1 \leq j \leq n} \mathbf{c}_j$ (observe that by minimality, all \mathbf{c}_j are join-irreducible), there are a positive integer k and a subdivision $x = z_0 < z_1 < \dots < z_k = y$ in Λ such that each $\nu(z_i, z_{i+1})$ is contained in some \mathbf{c}_j . As \mathbf{p} is the only join-irreducible element of $\mathbf{B}(m, 2)$ that is not join-prime, it suffices to solve this problem in each case $\nu(x, y) = \bigvee_{1 \leq j \leq n} \mathbf{c}_j$ with $n \geq 2$, and $\nu(x, y) = \mathbf{p} < \bigvee_{1 \leq j \leq n} \mathbf{c}_j$.

We begin with the first case. As all the \mathbf{c}_j belong to $A \cup \{\mathbf{b}_1\}$ if $x > 0$ and to $A \cup \{\mathbf{b}_2\}$ if $y < 0$, our refinement problem has a solution if either $x > 0$ or $y < 0$ (because μ and μ' are V-measures to $\mathbf{B}(m, 1)$ and $\mathbf{B}'(m, 1)$, respectively). Suppose now that $x < 0$ and $y > 0$; set $x' := -x$. Then $\mu(0, x' \wedge y) = \nu(x, y) = \bigvee_{1 \leq j \leq n} \mathbf{c}_j$. We separate cases. If $x' \leq y$, then $\mu(0, x') = \bigvee_{1 \leq j \leq n} \mathbf{c}_j$ is a minimal join-covering with $n \geq 2$, thus $x' \leq m$ (this is because $\mu(0, m+1) = \mathbf{p}$) and our join-covering is equivalent, up to permutation, to $\nu(x, y) = \bigvee_{1 \leq j \leq x'} \mathbf{a}_j$, for which a refinement is given by the subdivision $x < x+1 < \dots < -1 < y$, with successive measures $\nu(x, x+1) = \mathbf{a}_{x'}$, $\nu(x+1, x+2) = \mathbf{a}_{x'-1}$, \dots , $\nu(-2, -1) = \mathbf{a}_2$, $\nu(-1, y) = \mathbf{a}_1$. If $x' \geq y$, then $\mu(0, y) = \bigvee_{1 \leq j \leq n} \mathbf{c}_j$ is a minimal join-covering with $n \geq 2$, thus $y \leq m$ and our join-covering is equivalent, up to permutation, to $\nu(x, y) = \bigvee_{1 \leq j \leq y} \mathbf{a}_j$, for which a refinement is given by the subdivision $x < 1 < \dots < y-1 < y$, with successive measures $\nu(x, 1) = \mathbf{a}_1$, $\nu(1, 2) = \mathbf{a}_2$, \dots , $\nu(y-1, y) = \mathbf{a}_y$.

It remains to deal with the minimal join-coverings of the form $\nu(x, y) = \mathbf{p} < \bigvee_{1 \leq j \leq n} \mathbf{c}_j$. Necessarily, $x = -m-1$, $y = m+1$, and our covering is equivalent, up to permutation, to a covering of the form

$$\nu(-m-1, m+1) = \mathbf{p} < \mathbf{a}_1 \vee \mathbf{a}_2 \vee \dots \vee \mathbf{a}_m \vee \mathbf{b}_l, \quad \text{for some } l \in \{1, 2\}.$$

If $l = 1$, then a refinement is given by $-m-1 < 1 < 2 < \dots < m < m+1$, with successive measures $\mathbf{a}_1, \mathbf{a}_2, \dots, \mathbf{a}_m, \mathbf{b}_1$. If $l = 2$, then a refinement is given by $-m-1 < -m < -m+1 < \dots < -1 < m+1$, with successive measures $\mathbf{b}_2, \mathbf{a}_m, \mathbf{a}_{m-1}, \dots, \mathbf{a}_1$. \square

In particular, it follows from Proposition 10.8 that $\mathbf{B}(2, 2)$ has a lattice embedding into $\mathbf{P}_{\{4,5\}}(6)$, thus into $\mathbf{P}(6)$. It can be shown that $\mathbf{B}(2, 2)$ has no lattice embedding into $\mathbf{P}(n)$, for $n \leq 5$.

11. A LATTICE THAT CANNOT BE EMBEDDED INTO ANY PERMUTOHEDRON

The main goal of the present section is to provide a proof of the following result, which implies that *not every finite bounded lattice can be embedded into a permutohedron*.

Theorem 11.1. *The lattice $B(3, 3)$ cannot be embedded into any permutohedron.*

In order to prove Theorem 11.1, we denote, as in earlier sections, the join-irreducible elements of $B(3, 3)$ by $\mathbf{a}_1, \mathbf{a}_2, \mathbf{a}_3, \mathbf{b}_1, \mathbf{b}_2, \mathbf{b}_3$, and \mathbf{p} , with $\mathbf{a}_i < \mathbf{p}$ for each $i \in \{1, 2, 3\}$. We also set $\mathbf{a} := \mathbf{a}_1 \vee \mathbf{a}_2 \vee \mathbf{a}_3$. We suppose that there exists a lattice embedding $\varphi: B(3, 3) \hookrightarrow P(\ell)$ for some positive integer ℓ . Now $P(\ell)$ is a subdirect product of its associated Cambrian lattices $P_U(\ell)$ (cf. Proposition 6.7), thus, as $B(3, 3)$ is subdirectly irreducible (cf. Jipsen and Rose [16, Theorem 4.17]), there is a lattice embedding $\psi: B(3, 3) \hookrightarrow P_U(\ell)$ for some $U \subseteq [\ell]$. Now we define a new lattice K by setting

$$K := \begin{cases} B(3, 3), & \text{if } \psi(1_{B(3,3)}) = 1_{P_U(n)}, \\ B(3, 3) \cup \{\infty\}, & \text{otherwise,} \end{cases}$$

and we extend ψ to K by setting $\psi(\infty) := 1_{P_U(n)}$ (in case $\psi(1_{B(3,3)}) \neq 1_{P_U(n)}$). Now ψ is an unit-preserving lattice embedding from K into $P_U(\ell)$. By Proposition 10.6, the range of the dual U -polarized measure $\mu: \mathcal{I}_\ell \rightarrow K$ generates K as a $(\vee, 0)$ -semilattice.

In particular, \mathbf{p} is a join of elements in the range of μ . As \mathbf{p} is join-irreducible, it follows that there exists $(x, y) \in \mathcal{I}_\ell$ such that $\mathbf{p} = \mu(x, y)$. Pick such an (x, y) with $y - x$ minimal. For each $i \in [3]$, we say that a subdivision $x = z_0 < z_1 < \dots < z_n = y$ is *subordinate to \mathbf{b}_i* if

$$\text{either } \mu(z_j, z_{j+1}) \leq \mathbf{b}_i \text{ or } \mu(z_j, z_{j+1}) \leq \mathbf{a}_l \text{ for some } l \in [3], \text{ for each } j < n. \quad (11.1)$$

As μ is a V -measure and $\mu(x, y) = \mathbf{p} \leq \mathbf{a}_1 \vee \mathbf{a}_2 \vee \mathbf{a}_3 \vee \mathbf{b}_i$, there exists certainly such a subdivision. Observe that as $\mathbf{p} \leq \mathbf{a}_1 \vee \mathbf{a}_2 \vee \mathbf{a}_3 \vee \mathbf{b}_i$ is a minimal covering, each element of $\{\mathbf{a}_1, \mathbf{a}_2, \mathbf{a}_3, \mathbf{b}_i\}$ appears at least once among the elements $\mu(z_j, z_{j+1})$. In particular, $n \geq 4$.

Recall that U^c denotes the complement of U . Say that a *peak index* of a subdivision $x = z_0 < z_1 < \dots < z_n = y$ is an index $j \in [0, n-1]$ such that $z_j \in U \cup \{x\}$ and $z_{j+1} \in U^c \cup \{y\}$. We shall call the pair (z_j, z_{j+1}) the *peak associated to j* .

Lemma 11.2. *Let $i \in [3]$. Each subdivision $x = z_0 < z_1 < \dots < z_n = y$ subordinate to \mathbf{b}_i has a peak index. Furthermore, $\mu(x, z_j) \leq \mathbf{a}$ and $\mu(z_{j+1}, y) \leq \mathbf{a}$ while $\mu(z_j, z_{j+1}) \leq \mathbf{b}_i$, for each peak index j .*

Note. In the statement above, we are using again the convention $\mu(z, z) := 0$ for each $z \in [\ell]$.

Proof. If $z_j \in U \cup \{x\}$ for some $j \in [0, n-1]$, then, taking the largest such j , we obtain that $z_{j+1} \in U^c \cup \{y\}$. On the other hand, if $z_{j+1} \in U^c \cup \{y\}$ for some $j \in [0, n-1]$, then, taking the least such j , we obtain that $z_j \in U \cup \{x\}$. In both cases, j is a peak index; thus such an index always exists.

Let j be a peak index. From μ being an U -polarized measure it follows that $\mu(x, z_j) \leq \mathbf{p}$ and $\mu(z_{j+1}, y) \leq \mathbf{p}$. Therefore, by the minimality assumption on $y - x$,

it follows that $\mu(x, z_j) \leq \mathbf{a}$ and $\mu(z_{j+1}, y) \leq \mathbf{a}$, hence

$$\mathbf{p} = \mu(x, y) \leq \mu(x, z_j) \vee \mu(z_j, z_{j+1}) \vee \mu(z_{j+1}, y) \leq \mathbf{a} \vee \mu(z_j, z_{j+1}).$$

As $\mathbf{p} \not\leq \mathbf{a}$, it follows that $\mu(z_j, z_{j+1}) \not\leq \mathbf{a}$, thus, by (11.1), $\mu(z_j, z_{j+1}) \leq \mathbf{b}_i$. \square

Say that a subdivision subordinate to \mathbf{b}_i is *normal* if it has a peak index j such that for each $k \in [0, n-1] \setminus \{j\}$ there exists $l \in [3]$ such that $\mu(z_k, z_{k+1}) \leq \mathbf{a}_l$.

Lemma 11.3. *There exists a normal subdivision subordinate to \mathbf{b}_i , for each index $i \in [3]$. Furthermore, for each such subdivision $x = z_0 < z_1 < \dots < z_n = y$ and each $k \in [n-1]$, $k \leq j$ implies that $z_k \in U$ while $j+1 \leq k$ implies that $z_k \in U^c$.*

Note. This implies, of course, that the peak index of a normal subdivision is unique.

Proof. By Lemma 11.2, every subdivision $x = z_0 < z_1 < \dots < z_n = y$ subordinate to \mathbf{b}_i has a peak index j , while $\mu(x, z_j) \leq \mathbf{a}$ and $\mu(z_{j+1}, y) \leq \mathbf{a}$. As $\mathbf{a} = \mathbf{a}_1 \vee \mathbf{a}_2 \vee \mathbf{a}_3$ and as μ is a V-measure, there are natural numbers p, q and decompositions $x = s_0 < s_1 < \dots < s_p = z_j$ and $z_{j+1} = s_{p+1} < s_{p+2} < \dots < s_{p+q+1} = y$ such that for each $k \in [0, p+q] \setminus \{p\}$ there exists $l \in [3]$ such that $\mu(s_k, s_{k+1}) \leq \mathbf{a}_l$. Obviously, the subdivision

$$x = s_0 < s_1 < \dots < s_p < s_{p+1} < \dots < s_{p+q+1} = y$$

is normal, with p as a peak index.

Now let $x = z_0 < z_1 < \dots < z_n = y$ be a normal subdivision subordinate to \mathbf{b}_i , with peak index j , and let $k \in [n-1]$. Suppose first that $k \leq j$. If $z_k \in U^c$, then, as μ is an U -polarized measure, $\mu(z_k, y) \leq \mu(x, y) = \mathbf{p}$, thus, by the minimality assumption on $y - x$, $\mu(z_k, y) \leq \mathbf{a}$. However, from $\mu(z_l, z_{l+1}) \leq \mathbf{a}$ for each $l < k$ it follows that $\mu(x, z_k) \leq \mathbf{a}$, thus

$$\mathbf{p} = \mu(x, y) \leq \mu(x, z_k) \vee \mu(z_k, y) \leq \mathbf{a},$$

a contradiction. It follows that $z_k \in U$. Likewise, $j+1 \leq k$ implies that $z_k \notin U$. \square

Now Lemma 11.3 ensures that for each $i \in [3]$, there exists a normal subdivision $x = z_0^i < z_1^i < \dots < z_{n_i}^i = y$ subordinate to \mathbf{b}_i . Set $Z_i := \{z_j^i \mid 0 \leq j \leq n_i\}$ and denote by (s_i, t_i) the unique peak of that subdivision; so $x \leq s_i < t_i \leq y$.

Lemma 11.4. *Let $i, j \in [3]$ be distinct. If $t_i \leq t_j$, then $\mu(t_j, y) \leq \mathbf{a}_l$ for some $l \in [3]$.*

Proof. If $t_j = y$, then the conclusion holds trivially. Thus suppose that $t_j < y$. As (s_j, t_j) is a peak, $t_j \in U^c$. Moreover, $t_i < y$, thus $t_i \leq z_{n_i-1}^i < y$. As (s_i, t_i) is a peak and the subdivision associated to Z_i is normal, it follows that $\mu(z_{n_i-1}^i, y) \leq \mathbf{a}_l$ for some $l \in [3]$.

We claim that $z_{n_i-1}^i < t_j$. Suppose otherwise, that is, $t_j \leq z_{n_i-1}^i$. As x and $z_{n_i-1}^i$ both belong to Z_i , the inequality $\mu(x, z_{n_i-1}^i) \leq \mathbf{a} \vee \mathbf{b}_i$ holds. Now $t_i = z_m^i$ for some $m \in [n_i - 1]$, thus, as the subdivision associated to Z_i is normal,

$$\mu(t_i, z_{n_i-1}^i) \leq \bigvee_{m \leq k < n_i-1} \mu(z_k^i, z_{k+1}^i) \leq \mathbf{a}.$$

It follows that

$$\begin{aligned} \mu(t_j, z_{n_i-1}^i) &\leq \mu(t_i, z_{n_i-1}^i) && \text{(because } t_i \leq t_j \leq z_{n_i-1}^i \text{ and } t_j \in U^c) \\ &\leq \mathbf{a}. \end{aligned}$$

As $\mu(x, t_j) \leq \mathbf{a} \vee \mathbf{b}_j$ (because x and t_j both belong to Z_j), it follows that $\mu(x, z_{n_i-1}^i) \leq \mu(x, t_j) \vee \mu(t_j, z_{n_i-1}^i) \leq \mathbf{a} \vee \mathbf{b}_j$. Therefore, $\mu(x, z_{n_i-1}^i) \leq (\mathbf{a} \vee \mathbf{b}_i) \wedge (\mathbf{a} \vee \mathbf{b}_j) = \mathbf{p}$, thus, by the minimality statement on $y - x$, we get $\mu(x, z_{n_i-1}^i) \leq \mathbf{a}$. As $\mu(z_{n_i-1}^i, y) \leq \mathbf{a}_l$, it follows that $\mathbf{p} = \mu(x, y) \leq \mu(x, z_{n_i-1}^i) \vee \mu(z_{n_i-1}^i, y) \leq \mathbf{a}$, a contradiction.

By the claim above, $z_{n_i-1}^i < t_j$. As $t_j \in U^c$, it follows that $\mu(t_j, y) \leq \mu(z_{n_i-1}^i, y) \leq \mathbf{a}_l$. \square

The following dual version of Lemma 11.4 can be proved likewise.

Lemma 11.5. *Let $i, j \in [3]$ be distinct. If $s_i \leq s_j$, then $\mu(x, s_i) \leq \mathbf{a}_k$ for some $k \in [3]$.*

Now we can conclude the proof of Theorem 11.1. We may assume without loss of generality that $t_1 \leq t_2 \leq t_3$. It follows from Lemma 11.4 that $\mu(t_2, y) \leq \mathbf{a}_l$ for some $l \in [3]$. As $t_2 \leq t_3 \leq y$ and $t_3 \in U^c \cup \{y\}$, it follows that $\mu(t_3, y) \leq \mu(t_2, y) \leq \mathbf{a}_l$.

Next, suppose that $s_2 \leq s_3$. It follows from Lemma 11.5 that $\mu(x, s_2) \leq \mathbf{a}_k$ for some $k \in [3]$, so

$$\mathbf{p} = \mu(x, y) \leq \mu(x, s_2) \vee \mu(s_2, t_2) \vee \mu(t_2, y) \leq \mathbf{a}_k \vee \mathbf{a}_l \vee \mathbf{b}_2,$$

a contradiction. On the other hand, if $s_3 \leq s_2$, then, again by Lemma 11.5, $\mu(x, s_3) \leq \mathbf{a}_k$ for some $k \in [3]$, so

$$\mathbf{p} = \mu(x, y) \leq \mu(x, s_3) \vee \mu(s_3, t_3) \vee \mu(t_3, y) \leq \mathbf{a}_k \vee \mathbf{a}_l \vee \mathbf{b}_3,$$

a contradiction again. This completes the proof of Theorem 11.1.

By combining the result of Theorem 11.1 with those of Proposition 3.6, Lemma 9.2, and Proposition 10.8, we obtain the following analogue, for permutohedra, of Theorem 10.7.

Theorem 11.6. *Let m and n be natural numbers. Then the lattice $\mathbf{B}(m, n)$ embeds into some permutohedron iff either $m \leq 2$ or $n \leq 2$.*

12. A LARGE PERMUTOHEDRON WITH A PREIMAGE OF $\mathbf{B}(3, 3)$

After several unsuccessful attempts to turn Theorem 11.1 to an identity holding in all permutohedra while failing in $\mathbf{B}(3, 3)$, we (the authors of the present paper) started wondering whether it could actually be the case that $\mathbf{B}(3, 3)$ satisfies every lattice-theoretical identity satisfied by all permutohedra! The goal of the present section is to provide a proof that this guess was correct.

In order to do this, we shall need the notion of *splitting identity* of a finite, bounded, subdirectly irreducible lattice. Such lattices are often called *splitting lattices* (after McKenzie [20], see also Freese, Ježek, and Nation [8]). It is a classical result of lattice theory (cf. Freese, Ježek, and Nation [8, Corollary 2.76]) that for every splitting lattice K , there exists a largest lattice variety \mathcal{C}_K which is maximal with respect to not containing K as a member. Furthermore, \mathcal{C}_K can be defined by a single lattice identity, called a *splitting identity* for K , and there is an effective way to compute such an identity.

We shall apply this algorithm (given by [8, Corollary 2.76]) to the six-element set $X := \{x_1, x_2, x_3, y_1, y_2, y_3\}$, the lattice $\mathbf{B}(3, 3)$, with $u := \mathbf{p}$ and $v := \mathbf{a} = \mathbf{a}_1 \vee \mathbf{a}_2 \vee \mathbf{a}_3$, and the unique lattice homomorphism $f: \mathbf{F}_{\mathbf{L}}(X) \rightarrow \mathbf{B}(3, 3)$ such that $f(x_i) = \mathbf{a}_i$ and $f(y_i) = \mathbf{b}_i$ for each $i \in [3]$ (where $\mathbf{F}_{\mathbf{L}}(X)$ denotes the free lattice on X). From $\mathbf{p} = \bigwedge_{j \in \{1, 2\}} (\mathbf{a}_1 \vee \mathbf{a}_2 \vee \mathbf{a}_3 \vee \mathbf{b}_j)$ it follows that f is surjective.

For each $i \in [3]$, denote by i' and i'' the other two elements of $[3]$. We introduce new lattice terms by

$$\begin{aligned} x &:= x_1 \vee x_2 \vee x_3, & y &:= y_1 \vee y_2 \vee y_3, \\ \hat{x}_i &:= x_{i'} \vee x_{i''} \vee y, & \hat{y}_i &:= y_{i'} \vee y_{i''} \vee x, \end{aligned} \quad \text{for each } i \in [3],$$

and the corresponding elements of $B(3, 3)$,

$$\begin{aligned} a &:= a_1 \vee a_2 \vee a_3, & b &:= b_1 \vee b_2 \vee b_3, \\ \hat{a}_i &:= a_{i'} \vee a_{i''} \vee b, & \hat{b}_i &:= b_{i'} \vee b_{i''} \vee a, \end{aligned} \quad \text{for each } i \in [3].$$

The 0th stage β_0 of the lower limit table (cf. Freese, Ježek, and Nation [8, Theorem 2.4]) on the join-irreducible elements of $B(3, 3)$ is given by

$$\beta_0(a_i) = x_i \text{ and } \beta_0(b_i) = y_i \quad \text{for each } i \in [3], \quad \beta_0(p) = 1.$$

Then, using the only minimal join-coverings of $B(3, 3)$, namely $p < a_1 \vee a_2 \vee a_3 \vee b_j$ for each $j \in [3]$, we obtain the first stage β_1 of the lower limit table of $B(3, 3)$ on the join-irreducible elements of $B(3, 3)$:

$$\begin{aligned} \beta_1(a_i) &= \beta_0(a_i) = x_i, \\ \beta_1(b_i) &= \beta_0(b_i) = y_i, \end{aligned}$$

while

$$\begin{aligned} \beta_1(p) &= \bigwedge_{j=1}^3 (\beta_0(a_1) \vee \beta_0(a_2) \vee \beta_0(a_3) \vee \beta_0(b_j)) \\ &= \bigwedge_{j=1}^3 (x_1 \vee x_2 \vee x_3 \vee y_j). \end{aligned}$$

As $D_1(B(3, 3)) = B(3, 3)$, it follows from [8, Lemma 2.7] that $\beta = \beta_1$.

Similar calculations yield the upper limit table for $B(3, 3)$ on the meet-irreducible elements of $B(3, 3)$:

$$\begin{aligned} \alpha_0(\hat{a}_i) &= \hat{x}_i, & \alpha_0(\hat{b}_i) &= \hat{y}_i, & \alpha_0(a) &= x, \\ \alpha_1(\hat{a}_i) &= \alpha_0(\hat{a}_i) = \hat{x}_i, & \alpha_1(\hat{b}_i) &= \alpha_0(\hat{b}_i) = \hat{y}_i, \\ \alpha_1(a) &= x \vee \bigvee_{i=1}^3 (\hat{x}_i \wedge \hat{y}_1 \wedge \hat{y}_2 \wedge \hat{y}_3). \end{aligned}$$

Furthermore, as obviously

$$x_{i'} \vee x_{i''} \leq \hat{x}_i \wedge \hat{y}_1 \wedge \hat{y}_2 \wedge \hat{y}_3,$$

we obtain $x \leq \bigvee_{i=1}^3 (\hat{x}_i \wedge \hat{y}_1 \wedge \hat{y}_2 \wedge \hat{y}_3)$, thus

$$\alpha_1(a) = \bigvee_{i=1}^3 (\hat{x}_i \wedge \hat{y}_1 \wedge \hat{y}_2 \wedge \hat{y}_3).$$

As $D_1(B(3, 3)^{\text{op}}) = B(3, 3)^{\text{op}}$, it follows that $\alpha = \alpha_1$.

Consequently, by Freese, Ježek, and Nation [8, Corollary 2.76], a splitting identity for $B(3, 3)$ is given by

$$\bigwedge_{1 \leq j \leq 3} (x_1 \vee x_2 \vee x_3 \vee y_j) \leq \bigvee_{1 \leq i \leq 3} (\hat{x}_i \wedge \hat{y}_1 \wedge \hat{y}_2 \wedge \hat{y}_3). \quad (12.1)$$

While all the splitting identities for $B(3, 3)$ are equivalent, we shall work with the one given by (12.1). We obtained the example underlying Theorem 12.1 with the assistance of the **Mace4** component of the **Prover9 - Mace4** software, see McCune [19].

Theorem 12.1. *Set $U := \{5, 6, 9, 10, 11\}$. Then the Cambrian lattice $P_U(12)$ does not satisfy the identity (12.1). Consequently, $B(3, 3)$ is the homomorphic image of a sublattice of $P_U(12)$.*

Proof. We consider the elements $\mathbf{a}_1, \mathbf{a}_2, \mathbf{a}_3, \mathbf{b}_1, \mathbf{b}_2$, and \mathbf{b}_3 of $P_U(12)$ defined as

$$\begin{aligned}\mathbf{a}_1 &:= \langle 1, 5 \rangle_U \vee \langle 2, 3 \rangle_U \vee \langle 8, 12 \rangle_U \vee \langle 10, 11 \rangle_U; \\ \mathbf{a}_2 &:= \langle 3, 4 \rangle_U \vee \langle 5, 9 \rangle_U; \\ \mathbf{a}_3 &:= \langle 4, 8 \rangle_U \vee \langle 9, 10 \rangle_U; \\ \mathbf{b}_1 &:= \langle 1, 2 \rangle_U; \\ \mathbf{b}_2 &:= \langle 6, 7 \rangle_U; \\ \mathbf{b}_3 &:= \langle 11, 12 \rangle_U.\end{aligned}$$

Due to the subdivisions

$$\begin{aligned}1 < 2 < 3 < 4 < 8 < 12, & \quad \text{with successive measures } \mathbf{b}_1, \mathbf{a}_1, \mathbf{a}_2, \mathbf{a}_3, \mathbf{a}_1, \\ 1 < 5 < 6 < 7 < 8 < 12, & \quad \text{with successive measures } \mathbf{a}_1, \mathbf{a}_2, \mathbf{b}_2, \mathbf{a}_3, \mathbf{a}_1, \\ 1 < 5 < 9 < 10 < 11 < 12, & \quad \text{with successive measures } \mathbf{a}_1, \mathbf{a}_2, \mathbf{a}_3, \mathbf{a}_1, \mathbf{b}_3,\end{aligned}$$

we obtain that the pair $(1, 12)$ belongs to $\bigwedge_{j=1}^3 (\mathbf{a}_1 \vee \mathbf{a}_2 \vee \mathbf{a}_3 \vee \mathbf{b}_j)$. On the other hand, evaluating the two sides of (12.1) at the \mathbf{a}_i s and \mathbf{b}_i s yields that $(1, 12)$ does not belong to the right hand side of the equation. Therefore, $P_U(12)$ does not satisfy (12.1).

As (12.1) is a splitting identity for $B(3, 3)$, it follows that $B(3, 3)$ belongs to the lattice variety generated by $P_U(12)$. As $P_U(12)$ is subdirectly irreducible (cf. Proposition 6.7), the final statement of Theorem 12.1 follows from Jónsson's Lemma (cf. Corollary 1.5 and Lemma 1.6 in Jipsen and Rose [16]). \square

Corollary 12.2. *The lattice $B(3, 3)$ satisfies every lattice-theoretical identity satisfied by $P_U(12)$, thus also every lattice-theoretical identity satisfied by the permutohedron $P(12)$. In particular, $B(3, 3)$ satisfies every lattice-theoretical identity satisfied by every permutohedron.*

13. OPEN PROBLEMS

Almost every nontrivial question about embedding finite lattices into associahedra, permutohedra, or related objects, is open, so we shall just list a few here. The most fundamental one seems to be whether it is decidable whether a given finite (bounded) lattice can be embedded into some associahedron (resp., permutohedron). Also, is the class of all sublattices of associahedra the intersection of a lattice variety with the class of all finite bounded lattices? In particular, if a lattice L can be embedded into some associahedron, is this also the case for all homomorphic images of L ? (By Theorems 11.1 and 12.1, the analogue of this problem for permutohedra has a negative answer.)

Another question, raised by the results of Sections 11 and 12, is the one whether there exists a nontrivial lattice-theoretical identity satisfied by all permutohedra.

Is the class of all identities satisfied by all associahedra (resp., permutohedra) decidable?

Does every closed interval of an associahedron (resp., a permutohedron) have a 0, 1-preserving lattice embedding into an associahedron (resp., a permutohedron)?

Caspard, Le Conte de Poly-Barbut, and Morvan proved in [6] that every finite Coxeter lattice (i.e., weak Bruhat order on a finite Coxeter group) is bounded. All the analogues for Coxeter lattices of the questions above are open as well. Can every finite Coxeter lattice be embedded into some permutohedron? (This is the case for Coxeter lattices of type B_n , but it needs to be worked out for the lattices of type D_n and for the other types.)

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